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MERJENJE IN OCENJEVANJE PRIJEMANJA V NAVIDEZNEM OKOLJU

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MEASUREMENT AND EVALUATION OF GRASPING IN VIRTUAL REALITY

PH.D. THESIS

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Leonardo da Vinci (1452-1519): Study of Hands, c. 1474

A man who works with his hands is a laborer; a man who works with his hands and his brain is a craftsman; but a man who works with his hands, his brain and his heart is an artist.

Louis Nizer (1902 – 1994)

Razširjeni povzetek

Pričujoče delo obravnava ocenjevanje in rehabilitacijo človeške roke z uporabo računalniško podprtih merilnih metod v virtualnem okolju. V uvodnem poglavju so podane nekatere pomembne lastnosti človeške roke, ki vplivajo na sposobnost prijemanja. Med njimi je najpomembnejša sposobnost upravljanja sile prstov, saj le-ta v veliki meri vpliva na stabilnost prijetega predmeta ter na spretnost pri manipulaciji s tem predmetom [71]. Meritve sile prijema imajo pomembno vlogo pri ocenjevanju funkcije roke v rehabilitaciji [53, 79, 101]. Na funkcionalnost prijema pa vpliva tudi izbira prijema. V disertaciji so predstavljene tri glavne klasifikacije prijemov, ki se nanašajo na pričujočo študijo. Prijeme delimo glede na zahteve naloge na močnostne in precizijske [86], glede na vrsto opozicije [45] ter glede na geometrijsko obliko prijema [19]. V nadaljevanju so opisane nekatere klinične metode, ki se uporabljajo za ocenjevanje funkcije roke na področju rehabilitacije. Izpostavljene so predvsem metode, kot sta Fugl-Meyerjev motorični test pri hemiplegičnih osebah [33] ter Jebsenov funkcijski test roke [49]. Oba testa se pogosto uporabljata pri ocenjevanju uspeha rehabilitacijskega posega pri različnih bolnikih, kot so osebe po poškodbi osrednjega živčnega sistema ali kapi ter bolniki z živčnomišičnimi boleznimi.

Pomembno vlogo v zadnjem času pridobivajo računalniško podprte meritve, s katerimi lahko izboljšamo občutljivost in objektivnost ocenjevanja. Številne študije so pokazale primernost rehabilitacije v računalniškem navideznem okolju, kjer osebe izvajajo številne naloge namenjene izboljšanju senzomotoričnih in funkcijskih sposobnosti [10, 42, 43, 48]. Prednost navideznega okolja je predvsem v fleksibilnosti nalog, ki so lahko prilagojene posameznikovim trenutnim sposobnostim. S primernim naborom nalog v navideznem okolju postane rehabilitacija tudi bolj zanimiva in prijazna tako pacientu kot tudi terapevtu (npr. urjenje v obliki računalniške igre). V disertaciji so predstavljene nekatere predhodne študije, kjer je bilo navidezno okolje uporabljeno za rehabilitacijo roke v ožjem smislu. V uvodnem poglavju so podane nekatere splošne zahteve in lastnosti, ki naj jih ima navidezno okolje namenjeno ocenjevanju in rehabilitaciji. Med njimi omenimo predvsem možnost predstavitve različnih situacij iz vsakdanjega življenja na način, ki je varen in razumljiv za uporabnika, možnost izbire različnih težavnostnih stopenj, ki spodbujajo bolnika k izboljšanju stanja, ter sočasno merjenje različnih parametrov, ki so nosilci informacije o napredku terapije [15]. Z računalniškim prikazom je mogoče predstaviti slabše funkcijske sposobnosti bolnika v večjem obsegu, s čimer bolnika motiviramo in spodbudimo k bolj aktivnemu sodelovanju pri rehabilitacijskem procesu. Pri osebah s poškodbami osrednjega živčnega sistema pa je še posebej pomembna povratna informacija pacientu, saj lahko intenzivno in ponavljajoče urjenje doprinese k reorganizaciji centralnega živčevja [12, 109].

V zaključku uvodnega poglavja sta podani dve shemi (Figure 3.1, Figure 3.2), ki strnjeno predstavljata splošen model računalniško podprte rehabilitacije ter rehabilitacije v navideznem okolju. Sistem računalniško podprte rehabilitacije sestavljajo trije podsistemi: senzorski, aktuatorski in kognitivni. Senzorski podsistem vključuje določanje različnih parametrov, ki vplivajo na funkcionalnost roke, kot so mobilnost prstov, sila prijema, geometrija prijema, odprtost prijema, navori v sklepih prstov, koordinacija sile ter drugi. Izmerjene rezultate lahko primerjamo s tistimi, dobljenimi prejšnje dni, in tako zasledujemo napredek terapevtskega posega. Dobljeni rezultati so lahko tudi v pomoč pri načrtovanju in razvoju aktivnih (aktuatorskih) sistemov, ki so namenjeni izboljšanju sposobnosti prijemanja. Aktuatorski podsistem vključuje funkcionalno električno stimulacijo mišic roke, aktivne ortoze, kjer krmiljeni motorji povzročajo gib prstov, haptične vmesnike ter različne rehabilitacijske robote, namenjene razgibavanju prstov in roke. Za terapijo je delovanje aktuatorskega sistema lahko predprogramirano, v zaprti zanki s senzorskim podsistemom, lahko pa je pod delnim ali popolnim nadzorom pacienta. Informacijo iz senzorskega podsistema pa lahko vodimo tudi v kognitivni podsistem. Naloga tega dela rehabilitacijkega sistema je posredovati izmerjeno informacijo pacientu in tako še dodatno izboljšati učinke terapevtskega postopka. Pri študiju prijemanja je še najbolj učinkovita vidna povratna informacija [42, 48].

Pri rehabilitaciji v navideznem okolju skušamo razdeliti naloge v dve skupini: naloge za urjenje ter naloge za ocenjevanje. Pri takšen pristopu so naloge za urjenje lahko kompleksnejše ter predvsem namenjene izboljšanju le določene aktivnosti (npr. pisanje, prijemanje majhnih predmetov, odpiranje plastenke), obenem pa prilagojene funkcijskim sposobnostim posameznika. Oseba z zmanjšanimi funkcijskimi sposobnostmi v navideznem okolju lahko opravlja različne naloge iz vsakdanjega življenja, ki jih v resničnem okolju ne bi mogla izvesti. Pri tem sodelujejo isti možganski centri kot pri realnih nalogah, le da je motorični odziv okrnjen. S takšnim pristopom dosežemo pozitiven učinek rehabilitacije in ni potrebno čakati, da bi bile motorične sposobnosti posameznika dovolj velike za izvajanje iste aktivnosti v resničnem okolju (npr. urjenje koordinacije prstov se lahko začne hkrati z urjenjem roke v celoti). Rehabilitacija prizadetega uda se tako začne že v zgodnji fazi. Ob reorganizaciji osrednjega živčnega sistema pričakujemo tudi hitrejše okrevanje motoričnih sposobnosti, tako da lahko urjenje v navideznem okolju hitreje povežemo z običajno vadbo.

Pri nalogah za ocenjevanje je želimo predvsem objektivno in natančno izmeriti napredek rehabilitacije, pri čemer nas zanima izbrani fizikalni parameter, ki neposredno izraža funkcionalno stanje bolnika (npr. maksimalna sila prijema, natančnost vodenja sile, obseg giba). Naloge za ocenjevanje motoričnih ter senzomotoričnih sposobnosti so običajno predstavljene v bolj abstraktni obliki, tako da je obremenitev kognitivnih sposobnosti manjša.

Ocenjevanje funkcije roke

Prijemanje je najpomembnejša in najzahtevnejša človekova gibalna dejavnost. Številne aktivnosti v vsakdanjem življenju so tesno povezane s sposobnostjo izvajanja različnih gibov prstov [71, 86]. Cilj večine nalog, ki vključujejo prijemanje, je zanesljiv in stabilen prijem [20]. Ta je v veliki meri odvisen od sil prstov, s katerimi človek učinkuje na predmet, ter sposobnosti prilagajanja sile glede na različne zunanje vplive. Naloge prijemanja zahtevajo usklajeno delovanje osrednjega živčnega sistema in številnih mišic v telesu. Pri osebah po poškodbah osrednjega živčnega sistema ali po fizičnih poškodbah skeletnega ter živčnomišičnega sistema roke v ožjem smislu pa je funkcijska sposobnost roke pogosto zmanjšana, kar v veliki meri vpliva na sposobnost opravljanja številnih vsakdanjih aktivnosti [33, 39, 121]. Študij prijemanja je tako pomemben tudi na področju diagnostike in rehabilitacije, kjer se na podlagi ocene funkcionalnosti roke predlaga ustrezna fizioterapija ali medikamentna terapija. Funkcionalnost roke opišemo kot sposobnost prijemanja in manipulacije z različnimi predmeti pri aktivnostih v vsakdanjem življenju [79]. Odvisna je predvsem od območja gibanja prstov in zapestja, sile prijema ter senzomotoričnih sposobnosti človeka. Za oceno funkcionalnosti roke se uporabljajo različni funkcionalni testi, kjer se ocenjuje sposobnost izvajanja nalog, povezanih s prijemanjem. Med najpogostejšimi testi, ki se uporabljajo v rehabilitaciji, so test aktivnosti iz vsakdanjega življenja (ADL) [79], Jebsenov test roke [49], Fugl-Meyerjev motorični test [33], manualni mišični test (MMT) [35] in drugi [103, 121]. Obstoječe metode za ocenjevanje funkcionalnosti roke večinoma dajejo le kvalitativno informacijo o bolnikovem stanju. Pri tem gre največkrat za precej subjektivno oceno terapevta, ki je v veliki meri odvisna od predhodno pridobljenih izkušenj [79]. Takšne metode tako ne omogočajo odkrivanja majhnih sprememb v funkcionalnosti roke, ki so posledica terapije ali napredovanja bolezni. Prav zato se pojavlja potreba po objektivnih in računalniško podprtih meritvah, ki lahko bistveno skrajšajo čas ocenjevanja, povečajo objektivnost in natančnost pridobljenih podatkov ter omogočajo enostavno dokumentacijo in spremljanje oseb skozi čas terapije.

Diagnoza bolezenskih znakov ali poškodb roke vključuje ocenjevanje in merjenje različnih parametrov, ki se nanašajo na fizične in dinamične lastnosti roke. Med najpogostejšimi metodami ocenjevanja funkcionalnosti v rehabilitaciji je meritev jakosti prijema kot informacija o maksimalni sili prijema [73, 79, 90]. Te meritve se izvajajo predvsem z različnimi mehanskimi merilniki sile (npr. z izometričnimi dinamometri), ki dajejo informacijo o velikosti sile prijema, ne pa tudi o dinamičnih spremembah ter usmerjenosti sile [47]. Ustrezna smer sile in dinamično prilagajanje sile na predmet glede na zahtevano nalogo pa v veliki meri vplivata na uspešen prijem in izvedbo naloge (npr. dinamično prilagajanje sile na svinčnik med pisanjem) [71, 119]. Merjenje maksimalne sile prijema tako daje le delno informacijo o funkcionalnosti roke [79]. Za večino aktivnosti v vsakdanjem življenju namreč zadoščajo že sile precej manjšega velikostnega reda (npr. do 40 N) [50], zato je bolj kot meritev maksimalne sile pomembna meritev funkcionalnih sil. Merilno območje mehanskih merilnikov sile je pogosto neprimerno za merjenje majhnih sil (npr. pod 10 N), ki so značilne pri osebah z živčnomišičnimi boleznimi [62]. Ocenjevanje lahko izboljšamo z dinamičnim merjenjem sile z elektronskimi merilniki, kjer izmerimo potek sile znotraj izbranega časovnega intervala. Tako je mogoče opraviti meritev z večjo natančnostjo, iz rezultatov pa lahko ocenimo tudi utrujanje mišic med izvajanjem prijema [53].

Pri merjenju sile prijema je potrebno upoštevati, da se merilniki pogosto po obliki in velikosti razlikujejo od predmetov, ki jih uporabljamo v vsakdanjem življenju. Sila prijema je namreč v veliki meri odvisna od vrste uporabljenega prijema ter fizičnih lastnosti predmeta (npr. oblike in velikosti). Funkcionalnost roke se tako kaže v sposobnosti izvajanja različnih prijemov ob ustrezni koordinaciji sile. Natančnejšo meritev sile dosežemo z uporabo elektronskih dinamometrov ter t.i. merilnih predmetov, ki so podobni predmetom iz vsakdanjega življenja, le da so opremljeni s senzorji sile. S časovno meritvijo sile pridobimo informacijo o pacientovi sposobnosti upravljanja sile, ki ima pomembno vlogo pri zagotavljanju stabilnega prijema. V literaturi najdemo različne primere uporabe merilnih predmetov za študij prijemanja. Memberg in Crago [80] sta izdelala predmeta v obliki knjige in žlice za kvantitativno vrednotenje funkcionalnosti roke. Chadwick in Nicol [16] sta analizirala vektorje sil pri različnih prijemih. Peebles in

Norris [89] sta predstavili študijo merjenja izometričnih sil pri različnih aktivnostih vsakdanjega življenja ter analizirali vpliv starosti osebe na maksimalno uporabljeno silo. Vpliv oblike in velikosti predmeta na silo prijema je raziskal Amis [2], o vplivu mase na dinamični potek sile prijema pa poroča Westling [114].

Raziskave so pokazale, da lahko učinke terapije povečamo z uvedbo kognitivne povratne informacije bolniku. Ta lahko predstavlja le informacijo o napredku ob terapiji ali pa v neposredni povezavi z merilnim sistemom predstavlja del terapije bolniku. Primerne metode za ocenjevanje in urjenje motoričnih sposobnosti so različne naloge sledenja [51], kjer oseba izvaja določen gib ali silo glede na povratno informacijo (npr. vidna informacija z računalniškega zaslona). Med uporabljenimi pristopi raziskovalci pogosto posegajo tudi po nalogah v navideznih okoljih, ki poskušajo posnemati naloge iz vsakdanjega življenja [11, 36, 48].

Pregled področja

V rehabilitaciji je smiselna uporaba kognitivne informacije, ki jo posredujemo pacientu, saj na tak način lahko povečamo učinek terapije [39, 48, 93, 109]. Pri metodah sledenja lahko z ustrezno izbrano obliko povratne informacije »predpišemo« pacientu želen gib oziroma silo, ki naj jo izvaja. Ovrednotena razlika med želeno in doseženo vrednostjo predstavlja kvantitativen kriterij, ki neposredno izraža pacientove senzomotorične sposobnosti [51]. Metodo je tako mogoče uporabiti tudi za ocenjevanje funkcionalnega stanja roke, ki je lahko v pomoč pri vrednotenju učinkov drugih pristopov terapije [63]. Oseba ob izvajanju naloge skuša izboljšati svoje trenutno stanje in doseči čim boljše rezultate, kar ima hkrati tudi pozitiven terapevtski učinek. Naloge sledenja so v veliki meri podobne klasičnim rehabilitacijskim pristopom, kjer fizioterapevt vodi bolnika skozi različne naloge, ki zahtevajo ustrezen motoričen odziv. Pri računalniških nalogah je ocena o sposobnostih pacienta bolj objektivna, saj so posamezni testi bolj ponovljivi in meritve natančnejše, rezultat testiranja pa predstavlja kvantitativno vrednost, ki jo lahko neposredno povežemo tudi s fizikalnimi parametri (npr. premik, sila, navor) [102].

Naloge sledenja se uporabljajo predvsem pri različnih raziskavah v psihologiji, kjer je poudarek na zaznavanju in razumevanju vidnih signalov [51, 115]. Podobne naloge se uporabljajo pri ocenjevanju senzomotoričnih odzivov na številnih drugih raziskovalnih področjih, kot so vojaška in civilna industrija, medicina, rehabilitacija, psihofarmakologija in druge. Na področju prijemanja je v naloge smisleno vključiti silo prijema, saj poleg mobilnosti prstov v veliki meri vpliva na funkcionalnost roke [79]. Kriz in ostali [59] so metodo sledenja uporabili kot trening pri rehabilitaciji oseb po poškodbi glave, kjer so se pokazali pozitivni rezultati takšne terapije. Blank in sodelavci [4, 5] pa so z metodo sledenja sile prijema analizirali razvoj sposobnosti upravljanja sile roke pri otrocih od 3. do 6. leta. Vaillancourt s sodelavci [111] ter Kunesch in ostali [60] so ocenjeval vpliv vidne povratne informacije na izvajanje sile pri osebah s Parkinsonovo boleznijo, kjer so zaznali pozitiven vpliv kognitivne informacije na produkcijo sile v primerjavi z rezultati brez povratne informacije.

Večina omenjenih študij je metodo sledenja uporabila predvsem za analizo senzoričnega zaznavanja. Študije, ki so obravnavale sledenje sile prstov, so ocenjevale odzive pri pincetnem prijemu [4, 59], ne pa tudi pri ostalih načinih prijemanja. Za ocenjevanje funkcije roke je torej smiselno vrednotiti koordinacijo sile pri različnih funkcionalnih prijemih, saj lega prstov in roke glede na predmet v veliki meri vpliva na sposobnost upravljanja sile [54, 101, 119]. Izmerjeni odzivi pri posameznih prijemih neposredno izražajo senzomotorične sposobnosti osebe pri nadzoru posameznih mišičnih skupin. To je še posebej pomembno pri osebah z živčnomišičnimi boleznimi, kjer so posamezne mišične skupine roke različno prizadete [121]. Ocenjevanje utrujanja mišic in sposobnosti upravljanja sile prstov z metodo sledenja tako podaja kvantitativno in objektivno informacijo o posameznem načinu prijemanja [62].

Pri osebah po poškodbi glave ter po kapi pa se poleg zmanjšanja funkcijskih sposobnosti največkrat pojavi tudi pomanjkanje senzornih informacij zaradi poškodbe osrednjega živčnega sistema [33, 94]. S kognitivno povratno informacijo in terapijo, ki vključuje uporabo različnih senzomotoričnih centrov v osrednjem živčnem sistemu, lahko pričakujemo izboljšanje stanja [59, 93]. Pri tem gre po eni strani za fizično urjenje različnih mišičnih skupin, ki vodi k povečanju jakosti ter izboljšanju kvalitete prijema, po drugi strani pa lahko pričakujemo tudi izboljšanje bolnikovih senzomotoričnih sposobnosti v celoti. Študije so namreč pokazale, da ob ustrezni terapiji lahko pride do reorganizacije živčnih povezav v osrednjem živčnem sistemu [109]. Navidezno računalniško okolje se je izkazalo kot primerno za rehabilitacijo, kjer so bolniki s ponavljajočim urjenjem izboljšali svoje senzomotorične sposobnosti [15, 81, 83]. Holden in sodelavci [43] so uporabili navidezno okolje in merilno rokavico za urjenje koordinacije prstov pri prijemanju in manipulaciji z majhnimi predmeti. Jack in sodelavci [48] so predstavili rehabilitacijski sistem s haptičnim vmesnikom in merilno rokavico, ki omogoča urjenje funkcije roke po poškodbi osrednjega živčnega sistema. Rezultati urjenja v navideznem okolju so pokazali, da so vse tri osebe po kapi, ki so bile vključene v raziskavo, izboljšale funkcijske sposobnosti roke tudi pri vsakdanjih aktivnostih.

Zastavljeni cilji in metodologija

Število raziskav s področja ocenjevanja in rehabilitacije roke v ožjem smislu je v primerjavi z ostalimi področji relativno majhno. Pri ocenjevanju funkcije roke želimo predvsem pridobiti čim bolj objektivne in zanesljive podatke, ki pričajo o napredovanju bolnika skozi čas terapije oziroma zmanjšanju funkcijskih sposobnosti zaradi bolezni ali poškodbe. Med najpomembnejšimi parametri, ki vplivajo na funkcionalnost roke, sta prav gotovo sila prijema ter sposobnost upravljanja sile prstov na prijet predmet. V pričujoči študiji je predstavljena uporaba računalniških metod, kot so naloge sledenja in navidezna okolja, za ocenjevanje in rehabilitacijo koordinacije sile prstov pri različnih bolnikih. V prvem delu študije smo tako želeli ovrednotiti metodo sledenja sile prijema za ocenjevanje upravljanja sile, ki bi podajala kvantitativno in objektivno informacijo o bolnikovem stanju ob izbrani terapiji. Pri tem smo skušali upoštevati splošne zahteve, ki veljajo za ocenjevanje in vrednotenje funkcijskih sposobnosti v rehabilitaciji. Metoda ocenjevanja mora zagotavljati ponovljivost rezultatov, dovolj veliko občutljivost za zaznavanje majhnih sprememb, naloge pa morajo biti dovolj preproste za razumevanje tako pacientu kot tudi terapevtu [40]. V drugem delu naloge smo načrtali kompleksnejše navidezno okolje in izpopolnjeno napravo za merjenje sil posameznih prstov. Končni cilj je bil izdelati in preskusiti rehabilitacijski sistem v navideznem okolju, ki bi ga terapevti lahko samostojno uporabljali pri rehabilitaciji roke.

Ocenjevanje upravljanja sile prijema z metodo sledenja

V okviru prvega zastavljenega cilja smo načrtali in izdelali merilno napravo za merjenje sile prijema pri različnih funkcionalnih prijemih [61]. Naprava sestoji iz komercialnega senzorja sile in kovinskega ogrodja, na katerega je mogoče pritrditi merilne nastavke različnih oblik (npr. krogla, tanka plošča, valj). Oblika in velikost merilnih nastavkov je bila izbrana po Fugl-Meyerjevem funkcijskem testu roke [33]. Z napravo je tako mogoče ocenjevati osnovne prijeme, ki se najpogosteje uporabljajo pri vsakdanjih nalogah (npr. pincetni prijem za pisanje, cilindrični prijem kozarca, lateralni prijem pri uporabi žlice idr.). Merilna naprava je bila vključena v nalogo sledenja, kjer je pacient s prilagajanjem sile prijema sledil različnim tarčam na zaslonu. Pri nalogi je signal tarče prikazan z modrim obročem, njegova vertikalna lega pa ustreza trenutni vrednosti tarče. Izmerjena sila prijema je sočasno prikazana z rdečo piko na zaslonu. Pri povečevanju sile na merilni predmet se rdeča pika premika navzgor, pri popuščanju prijema pa proti izhodiščni legi. Opisana naloga sledenja zahteva, da s prilagajanjem sile čim natančneje sledimo spreminjajoči se legi tarče. Zahtevnost naloge lahko poljubno nastavljamo s spreminjanjem oblike signala tarče (npr. sinusna, pravokotna oblika), amplitude (t.j. velikosti sile) ter dinamičnih parametrov (npr. perioda, čas vzpona signala). Z omenjenimi parametri tako neposredno podajamo zahteve po velikosti in dinamiki sile prijema, ki naj jo oseba izvaja.

Pri kontrolni skupini 32 zdravih oseb smo želeli ugotoviti, kako se rezultati sledenja sile razlikujejo med različnimi starostnimi skupinami. Meritve smo opravili v skupini 10 letnih otrok, v skupini mlajših oseb od 25. do 35. leta starosti ter skupini oseb nad 50. letom starosti. Pri tem smo analizirali vpliv dominantnosti roke ter dinamike sledenja sile. V skupini mlajših oseb smo pridobili tudi rezultate sledenja sile pri različnih vrstah prijemov, ki so služili kot referenčna meritev za kasnejša merjenja z bolniki. Zanimala nas je tudi razlika med precizijskimi in močnostimi prijemi [86], kjer smo pričakovali večjo natančnost upravljanja sile pri precizijskih prijemih. Uporaba različnih prijemov je predvsem smiselna pri ocenjevanju bolnikov, kjer je funkcija posameznih mišic lahko različno prizadeta.

Metodo smo nadalje uporabili za ocenjevanje prijemanja in upravljanja sile pri bolnikih z živčnomišičnimi boleznimi [62]. Živčnomišične bolezni so progresivne bolezni, ki prizadenejo določene mišične skupine, lahko simetrično ali asimetrično, in povzročijo zmanjšanje mišične moči ter povečajo utrudljivost mišic [113]. Pri takšnih bolnikih je merjenje maksimalne sile prijema ter vrednotenje utrujanja posameznih mišičnih skupin pomemben parameter za ocenjevanje napredka bolezni [121]. Pri kliničnem vrednotenju funkcionalnosti roke se predvsem uporabljata merjenje maksimalne sile prijema ter manualni mišični test. V večini primerov so uporabljeni dinamometri za merjenje sile premalo natančni, da bi zaznali majhne spremembe v jakosti prijema. Z izdelano merilno napravo pa je mogoče izmeriti silo pri različnih funkcionalnih prijemih z natančnostjo pod 0.05 N. Metodo sledenja smo v skupini 20 bolnikov z različnimi živčnomišičnimi boleznimi uporabili za merjenje maksimalne sile, vrednotenje utrujanja mišic ter ocenjevanje sposobnosti upravljanja sile. Analizirali smo vpliv diagnoze na sposobnost upravljanja sile in posredno tudi na funkcijo roke v primerjavi s skupino zdravih oseb.

Predlagan ocenjevalni sistem smo uporabili tudi za vrednotenje učinka terapije z botulin-toksinom. Pri različnih ustaljenih metodah terapije (npr. funkcionalna električna stimulacija, medikamentna terapija) je pogosto potrebno ovrednotiti uspeh terapije pri posameznem bolniku skozi daljše časovno obdobje. Za objektivno vrednotenje je potrebna kvantitativna ocena o funkcionalnem stanju roke. Z opisano metodo sledenja sile smo tako spremljali morebitno izboljšanje upravljanja sile v prstih po terapiji z botulin-toksinom, ki se uporablja za zdravljenje spastičnosti pri osebah po kapi ali poškodbi glave, cerebralni paralizi ter multipli sklerozi [10, 21, 95]. Za študijo so bile izbrane tri osebe po poškodbi glave, vendar je bila zaradi tehničnih razlogov skozi celotni čas terapije spremljana le ena oseba, ki je prejela botulin-toksin za zmanjšanje spastičnosti fleksorjev roke. Pri tej osebi so bile izvedene mertive pred terapijo ter 6 in 13 tednov po terapiji [63].

Urjenje upravljanja sile prijema z metodo sledenja

V drugem delu študije smo sistem z metodo sledenja sile prijema uporabili kot terapevtski pripomoček za urjenje funkcije roke pri osebah po kapi. Številne študije [12, 39, 48, 93] so pokazale pozitiven učinek ponavljajočega izvajanja različnih nalog ob posredovani vidni povratni informaciji o izvajanju nalog bolniku. Pri ponavljanju različnih motoričnih nalog lahko pride do reorganizacije osrednjega živčnega sistema in s tem do ponovne vzpostavitve oziroma izboljšanja nadzora motoričnega odziva mišic. Za urjenje z metodo sledenja je bil na podlagi prve merilne naprave izdelan prepostejši merilni sistem za merjenje sile prijema z dvema merilnima enotama v obliki valja in tanke plošče. Merilni sistem omogoča boljšo prenosljivost ter preprostejšo uporabo kot prvi prototip. Izdelan je bil tudi programski vmesnik s podatkovno bazo, ki omogoča samodejno shranjevanje rezultatov urjenja. V študijo senzomotoričnega urjenja roke z metodo sledenja smo vključili 10 oseb po kapi, ki so se urile vsak dan v obdobju štirih tednov. V začetku urjenja in ob koncu vsakega tedna je bila za primerjavo meritev izvedena še na kontralateralni roki. Naloge sledenja so bile ob sodelovanju fizioterapevtov načrtane s ciljem povečevanja mišične jakosti, izboljšanja upravljanja sile ter izboljšanja odpiranja prijema, ki je zaradi spastičnosti pri osebah po kapi še posebej problematično [40]. Osebe so bile v času urjenja z metodo sledenja vključene v program običajne delovne terapije.

Navidezno okolje za ocenjevanje in rehabilitacijo roke

Cilj tretjega dela disertacije je bil razvoj bolj izpopolnjene merilne naprave, ki bi omogočala merjenje sil posameznih prstov. Izometrična naprava za prste je bila vključena v navidezno okolje za ocenjevanje in rehabilitacijo roke [64]. Za merjenje sil posameznih prstov so bili uporabljeni trije večdimenzionalni senzorji sile, ki omogočajo merjenje treh sil in treh navorov palca, kazalca ter sredinca. Napravo sestavlja ogrodje iz aluminija, na katero so pritrjeni senzorji, ter posebna držala za prste, ki omogočajo prenos sile s prsta na senzor [64]. Merilna naprava je bila izdelana v okviru evropskega projekta Alladin (6. okvirni program Evropske unije, pogodba: IST-2002-507424), katerega cilj je spremljanje napredka rehabilitacije pri osebah po kapi. Napravo smo želeli uporabiti kot vmesnik za večprstno prijemanje v navideznem okolju. Iz robotske literature [84, 85] smo privzeli matematični model večprstnega prijemanja, na podlagi katerega smo na izviren način izpeljali model prijemanja z izometrično napravo v navideznem okolju. Za izvajanje nalog prijemanja je bil uporabljen pristop psevdohaptičnosti [14, 65], kjer gre za predstavitev haptične informacije navideznega okolja z vidno ter taktilno povratno informacijo. Sile iz realnega okolja se tako preslikajo v ustrezen premik oziroma deformacijo v navideznem okolju. Izmerjene sile in navori posameznih prstov predstavljajo dotike na površini navideznega predmeta, ki se ustrezno odziva glede na skupno silo ter dinamični model okolja. Informacija o sili se predstavi uporabniku preko vidne povratne zveze ter taktilne informacije o trenutni izvajani sili prstov ob dotiku z napravo. Predmet v navideznem okolju je "vpet" med navidezne vzmeti in dušilke v vseh šestih prostostnih stopnjah, s čimer je določen dinamični odziv predmeta na zunanjo silo. Gibanje predmeta je tako mogoče omejiti v izbranih prostostnih stopnjah. Tako sta na primer pri rotaciji gumba aktivni le navidezna vzmet in dušilka okoli rotacijske osi gumba, ostale smeri gibanja pa so popolnoma omejene. Matematični model večprstnega prijemanja ter dinamični model okolja sta bila sprogramirana v programskem jeziku C in prikazana z uporabo grafičnega orodja Maverik [44]. Izdelana je bila splošna knjižnica, ki jo lahko uporabimo pri izvedbi različnih nalog v navideznem okolju skupaj z merilno napravo za prste. V navideznem okolju so posamezni dotiki prikazani z navideznimi prsti v obliki majhnih stožcev, ki določajo pozicijo ter orientacijo posameznega prsta glede na koordinatni sistem predmeta. Lega dotikov glede na predmet je tako vnaprej določena, prste pa je mogoče premikati vzdolž normale na površino predmeta. Ko se navidezni prsti dotaknejo površine predmeta, postanejo aktivni in lahko izvajajo silo na predmet v poljubni smeri. Predmet lahko potiskamo le z enim prstom ali pa ga primemo z dvema oziroma tremi prsti ter ga tako premikamo po navideznem prostoru.

V predstavljenem navideznem okolju so bile sprogramirane štiri naloge namenjene rehabilitaciji roke: (1) odpiranje sefa, (2) nalivanje vode, (3) stiskanje elastičnega obroča ter (4) naloga sledenja. Pri prvi nalogi je potrebno odpreti sef, tako da z obračanjem številčnice poiščemo ustrezno kombinacijo številk in črk. Gumb najprej primemo, nato pa s silo prstov v lateralni smeri ustvarimo ustrezen navor, ki zavrti gumb v novo lego. Naloga je zaključena, ko razrešimo prikazano kombinacijo v celoti ter tako odpremo vrata sefa. Pri drugi nalogi je potrebno s kozarcem napolniti vrč z vodo do označenega nivoja. Kozarec najprej primemo z vsemi tremi prsti, ga napolnimo z vodo, prenesemo nad vrč in vlijemo vodo iz kozarca. Premikanje kozarca v eno ali drugo smer dosežemo tako, da na prijet kozarec ustvarjamo skupno silo v izbrani smeri. Naloga zahteva natančno koordinacijo sile prstov in je tako najbolj kompleksna med predstavljenimi nalogami. Tretja naloga je namenjena urjenju in povečevanju jakosti prijema ob ponavljajoči mišični aktivnosti za odpiranje in zapiranje roke. V navideznem okolju je prikazan elastičen obroč, ki se deformira ob stiskanju. Njegovo elastičnost je mogoče poljubno nastavljati, s čimer vplivamo na silo, ki je potrebna, da obroč popolnoma deformiramo. Naloga zahteva, da z izmeničnim stiskanjem in popuščanjem sledimo barvi obroča, ki se spreminja iz modre v vijolično. Četrta naloga pa je naloga sledenja sile prijema, ki je namenjana predvsem ocenjevanju napredka urjenja. Pri tej nalogi oseba, podobno kot pri nalogah opisanih v prvem delu disertacije, skuša slediti prikazani tarči na zaslonu. Lega tarče se lahko spreminja po poljubnih signalih. Za ocenjevanje je bila izbrana sinusna tarča s spremenljivo frekvenco, ki se je izkazala kot dober pokazatelj sposobnosti upravljanja sile v predhodni študiji pri osebah po kapi [63].

Pri vseh nalogah v navideznem okolju se shranjujejo podatki o silah prstov, skupni sili in navoru na predmet ter legi predmeta, kar omogoča kasnejšo analizo posamezne meritve. Iz časovnih potekov je moč analizirati stopnjo koordinacije prstov ob posameznih fazah vsake od nalog. Poleg nalog v navideznem okolju pa je bil sprogramiran tudi vmesnik, ki pri izvedbi naloge omogoča samodejno shranjevanje rezultatov vsakodnevne terapije. Program shranjuje podatke v podatkovno bazo izvedeno v MS Accessu (Microsoft Corp., Redmond, WA), ki jo je mogoče pregledovati z različnimi programskimi paketi. Rezultate je moč sproti prikazati tudi v samem programskem vmesniku za urjenje, s čimer je terapevtu in bolniku omogočena povratna informacija o poteku rehabilitacije. V okviru disertacije so prikazani rezultati na skupini zdravih oseb ter pri eni osebi po kapi, ki predstavljajo izhodišče za nadaljnje meritve in urjenje bolnikov.

Rezultati in izvirni prispevki disertacije

Rezultate in nekatere izvirne prispevke disertacije bomo poskušali strniti v naslednjih točkah:

- Izdelana je bila izvirna merilna naprava za natančno in objektivno vrednotenje sile pri različnih funkcionalnih prijemih [61].
- Razvita je bila nova merilna metoda za ocenjevanje prijemanja z metodo sledenja sile. V skupini zdravih oseb smo analizirali vpliv starosti in dominantnosti roke na sposobnost upravljanja sile prijema. Rezultati so pokazali, da senzomotorične funkcije povezane s prijemanjem pri desetletnih otrocih še niso v celoti razvite. Pri mlajših odraslih je upravljanje sile najboljše, pri starejših pa pride do poslabšanja senzomotoričnih sposobnosti, ki zmanjšujejo spretnost v rokah. Študija pri zdravih osebah ni pokazala razlik v upravljanju sile med levo in desno roko, kar se sklada

tudi s predpostavkami iz literature [52].

- Z metodo sledenja smo ocenjevali upravljanje sile pri bolnikih z živčnomišičnimi boleznimi, kjer smo analizirali utrujanje mišic ter ocenjevali natančnost koordinacije sile pri različnih prijemih [62]. Pri večini bolnikov je bila natančnost največja pri cilindričnem in lateralnem prijemu. Rezultati niso pokazali razlik glede na dominantnost roke, razen pri bolnikih, ki imajo asimetrično prizadetost. Pri analizi rezultatov pa najverjetneje zaradi majhnega števila bolnikov ter same narave živčnomišičnih bolezni nismo našli povezav med specifično diagnozo in rezultati sledenja. V prihodnjih raziskavah bi lahko v večji skupini bolnikov naredili podrobnejšo analizo rezultatov ocenjevanja z metodo sledenja. Pri pregledu literature nismo našli nobene raziskave, kjer bi do sedaj analizirali sposobnost upravljanja sile prijema pri tej obliki prizadetosti mišic. Kvantitativna ocena sposobnosti bolnika z živčnomišično boleznijo je velikega pomena tudi za prihodnje raziskave, kjer bi lahko objektivno ocenjevali vpliv različnih terapevtskih metod na morebitno izboljšanje motoričnih lastnosti posameznih mišičnih skupin.
- V okviru ocenjevanja upravljanja sile je bila metoda sledenja uporabljena tudi za vrednotenje učinka terapije z botulin-toksinom pri bolnici po poškodbi glave [63]. Rezultati so pokazali, da se je po zdravljenju ob zmanjšani spastičnosti izboljšala natančnost upravljanja sile prizadete roke.
- Učinke kognitivne povratne informacije pri metodi sledenja sile pa smo vrednotili v skupini oseb po kapi, kjer je bilo pri osmih osebah od desetih opaziti znatno izboljšanje v sposobnosti upravljanja sile prijema po štiritedenski terapiji [63]. Iz rezultatov študije ugotavljamo, da bi bila metoda sledenja sile primerna za urjenje kordinacije prstov in upravljanja sile prijema. V prihodnosti pa bi bilo potrebno izvesti obsežnejšo študijo ter rezultate primerjati z rezultati nekaterih ustaljenih kliničnih metod (npr. motorični test po Fugl-Meyerju [33]).
- Rezultati omenjenih študij so bili nadalje uporabljeni za razvoj izvirne naprave za merjenje sil in navorov prstov pri dvoprstnih in troprstnih prijemih [64]. Izdelana izometrična naprava za prste omogoča merjenje sil in navorov prstov v vseh prostostnih stopnjah, s čimer je mogoče natančno ovrednotiti napredek terapije, namenjene izboljšanju koordinacije gibanja in upravljanja sile prstov.
- Merilna naprava za prste je bila uspešno vključena v navidezno okolje za ocenjevanje in rehabilitacijo roke, ki je namenjeno predvsem urjenju senzomotoričnih sposobnosti oseb po kapi. Pri tem je bil uporabljen pristop

psevdohaptičnosti [14, 65], kjer z vidno ter taktilno povratno informacijo osebi predstavimo silo v navideznem okolju. Z uporabo metod iz robotskega prijemanja smo preslikali sile in navore posameznih prstov na predmet ter tako z dinamičnim modelom simulirali ustrezen odziv navideznega predmeta na izvajano silo prstov. Izdelano je bilo izvirno navidezno okolje za urjenje skupaj z vmesnikom za shranjevanje in prikaz rezultatov. Pri pregledu literature na področju navidezne resničnosti in robotike nismo našli nobene študije, kjer bi bila izometrična naprava uporabljena za večprstno prijemanje predmetov v navideznem okolju. Predlagan pristop omogoča prijemanje in manipulacijo predmetov v navideznem okolju, ki zahteva podobno koordinacijo upravljanja sile prstov kot naloge v resničnem okolju. Predstavljeno napravo bi bilo mogoče v prihodnosti izdelati tudi s preprostejšimi senzorji, ki bi še vedno omogočali enako funkcionalnost, in jo uporabiti v rehabilitacijskem okolju za urjenje oseb po kapi ali poškodbi roke. Sistem za rehabilitacijo v navideznem okolju je bil uspešno preskušen na skupini zdravih oseb ter pri eni osebi po kapi.

Abstract

This thesis is focused on the assessment and rehabilitation of human grasping through measurement of force by using computerized methods in virtual environment. Objective and accurate assessment of hand function is needed to monitor and quantify patient's progress during therapy and to validate the outcome of the rehabilitation treatment. Many of the clinical methods used are often based on subjective and qualitative assessments made by a therapist which unable detection of small changes following therapy or progress of a disease. Computer-assisted methods can provide more sensitive and accurate measurements of different parameters affecting the hand function while reducing the examination time and resources. Furthermore, the measured values can be presented to a patient as cognitive feedback during the therapy. Several investigators have shown the beneficial effect of such feedback (e.g. visual feedback) on the rehabilitation process. The repetition of different visually guided motor tasks can initiate the relearning process inside the central nervous system and contribute to the improvement of motor control of the affected muscles. Virtual reality training has been successfully used for the rehabilitation and skill enhancement of the upper extremities. The majority of the previous studies dealing with rehabilitation of hand function in virtual reality were focused on the restoration of finger movement. In our study we investigated the assessment and rehabilitation of the grip force control which greatly affects the ability to grasp and manipulate objects.

In this dissertation we present a novel tracking system for the evaluation of grip force control. The system consists of a grip-measuring device with end-objects of different shapes which was used as input to a tracking task where the patient had to apply the grip force according to the visual feedback. We first investigated the effect of age and hand dominancy on the grip force control in 32 healthy subjects. The results in healthy subjects showed significant differences in grip force control among different age groups while no effect of hand dominancy was found. The presented force tracking method was further applied for the evaluation of the grip force control in 20 patients diagnosed with various neuromuscular diseases. Their performance was analyzed for different grip types and the patients were classified into two functional groups based on their tracking skills. The results suggest that in some patients the disease did not affect their grip force control despite evident muscular weakness.

The method was also applied in a case study to evaluate the effects of botulinum toxin treatment to reduce spasticity and possibly increase the grip force control in a patient after head injury. In this patient the method revealed noticeable effects of the therapy on the patient's tracking performance. The reduced spasticity after the treatment improved the accuracy of tracking. The side effect of botulinum toxin was decreased muscle strength of the affected hand.

The proposed grip force tracking system was further applied as a supplemental therapy to train hand function in 10 patients after stroke. Training with the tracking system showed considerable improvements in the grip force control in most patients suggesting the beneficial effect of such therapy. The presented tracking method is aimed to be used in connection with the existing rehabilitation therapies (e.g. physiotherapy, functional electrical stimulation, drug treatment) to follow the influence of the therapy on patient's muscular strength and grip force control.

The purpose of the third part of the study was to develop a new rehabilitation system for the assessment and training of multi-fingered grasping in virtual environment. We designed an isometric finger device to simultaneously assess forces applied by the thumb, index, and middle finger. Mathematical model of grasping, adopted from the analysis of multi-fingered robot hands, was applied to achieve multi-fingered interaction with virtual objects. We used the concept of pseudo-haptic feedback where the user was presented with visual cues and tactile feedback to acquire haptic information on the virtual environment. Four virtual reality tasks were developed with the aim to improve grip force coordination and increase muscle strength of patients after stroke through repetitive exercises. The tasks include opening of a safe, filling and pouring water from a glass, training of muscle strength with an elastic torus and grip force tracking task. The developed application allows virtual reality training with tasks of various difficulty levels and automated data storage to follow the progress of therapy for each individual patient. The presented virtual system was evaluated in a group of healthy subjects and a post-stroke patient.

Key words: biomechanics, grasping, hand, rehabilitation of hand, motor learning

1 Introduction

The study of human grasping has an important role in rehabilitation of hand function, design of man-machine interfaces and development of multi-fingered robotic grippers. The assessment of hand function is important for diagnosis and evaluation of rehabilitation process in patients suffering from neuromuscular diseases, central nervous system injury or hand injury [33, 40, 79]. In every day activities the hand is used to pick, place and manipulate different objects and to interact with the environment. With the increased use of technology in everyday life, man-machine interaction has become an important factor in many activities. Appropriate interface devices (e.g. keys, joysticks, haptic devices) have to be designed to suit human hand in the most adequate way, while reducing the stress on the joints and muscles. To improve the capabilities of industrial robotic manipulators, dexterous robotic hands with multiple fingers have been developed [19, 74]. Many of the designs are based on the properties of human hand [50]. The research of human hand and grasping has therefore become one of the major research areas in many laboratories for biomechanics, robotics and computer sciences. The focus of this dissertation is the assessment and rehabilitation of hand function using computerized measurements of force in virtual reality.

1.1 Assessment of Grasping in Rehabilitation

One of the major goals of rehabilitation is to make quantitative and qualitative improvements in daily activities in order to improve the quality of independent living [106]. Accurate assessment and measurements are important to correctly diagnose patient's functional state and to evaluate the progress of therapy [79]. Rehabilitation of the hand should include task-oriented training and repetition of different motor tasks with the aim to restore or improve hand function [12, 108, 117]. The training should begin in the early phase to maximize the chances of recovery. The intensity of the therapy has a positive effect on the rehabilitation progress although individual approach should be taken for each patient [99]. An important factor contributing to the success of rehabilitation is also patient's psychological response [40]. Patient's interest should be raised by applying various exercises during training. Many studies suggest that cognitive feedback associated with the performance of the training tasks can greatly contribute to the rehabilitation process [12, 39, 42, 48, 93]. This is especially important in patients with reduced sensory-motor functions. The cognitive feedback can be provided to a patient during the therapy or at the end of each session. Visual information is most often used for real-time feedback on task performance. The information can be presented by a simple two-dimensional or visually richer three-dimensional virtual environment.

To evaluate the effects of a therapeutic method, appropriate assessment procedure is needed to provide objective, quantitative and reproducible measurements of physical quantities reflecting improvement [18]. Assessment of hand functionality in rehabilitation is performed by different function tests evaluating the ability to perform various tasks which include grasping and manipulation of different objects [33, 35, 49, 79, 103]. The majority of the existing hand function tests consist of descriptive and semi-quantitative evaluation made by a therapist [79], which reduces the ability to detect small changes during the course of therapy or progressive disease. Computer assisted methods can greatly increase the accuracy and objectivity of the assessment while reducing the examination time and resources [102]. In the dissertation several methods used in clinical practice for the evaluation and restoration of hand function will be briefly reviewed. The focus will be given on the drawbacks of conventional methods and comparison will be made with computerized tools.

1.2 Virtual Reality in Rehabilitation

Virtual reality (VR) technology characterizes the human-computer interfaces that enable a user to interact with a synthetic environment which provides a sense of presence through visual, tactile, haptic and auditory cues [36, 66]. The virtual environment is represented with a three-dimensional model which defines geometric and physical properties of different virtual objects. With the implementation of real-time dynamics generator, the object parameters (e.g. position and orientation) and the physical properties of the virtual environment (e.g. friction, gravity) can be modified to influence interaction within the virtual world. Different interface devices can be used for interaction in VR, ranging from simple desktop mouse to complex multi-fingered haptic devices such as Cyberglove-

Cybergrasp system (Immersion Corporation[1], San Jose, CA). The most important aspect of VR applications is realistic visualization, which increases the level of presence in the synthetic environment. The level of presence defines how similar is an activity in virtual environment as compared to the same activity performed in every day life [15]. The visual information can be presented through immersive or non-immersive display technology [36]. In fully immersive VR the user is wearing a head-mounted display which provides a 3D full field of view on the virtual scene. In non-immersive technology the virtual environment is presented on a computer or projection screen, establishing much lower level of presence. The visualization can be further enhanced by other types of feedback such as haptic feedback on the forces inside the environment, tactile feedback on contact with virtual surfaces, body acceleration, vibrations, wind, smell and 3D sound.

VR technology was initially developed for entertainment industry and military simulations; recently, however, it is employed in many areas such as computer aided design (CAD), architecture, data visualization and different medical applications [36]. The medical applications of VR technology include education in medicine, surgical training, modeling, imaging, telesurgery and telemedicine, ergonomics, rehabilitation and assistance with disabilities. In recent years, the use of VR applications for skill enhancement and rehabilitation has been studied extensively in many different areas, such as motor rehabilitation and assessment (e.g. in stroke, paraplegia, Parkinson's disease and other disabilities), treatment of cognitive disorders (e.g. memory disorders, spatial disabilities), and in psychotherapy (e.g. treatment of different phobias and psychological disorders) [15, 23, 48, 83, 106].

VR application for rehabilitation has to provide increasing task complexity based on patient's abilities. It has to allow selection of different levels of difficulty to motivate the patient, provide feedback to the patient on success or failure, and offer stimulative environment to increase the effects of the training [15]. In contrast to conventional diagnostic and rehabilitative methods used, VR tasks allow full control of the training conditions, replication and simulation of real-life situations, high repeatability of the tasks, further off-line analysis of patient's performance (e.g. accuracy, execution time, movement planning), and use of various visual representations of the same task to reduce fatigue and increase attention span. In this way a patient can enhance his/her skills through a game-like environment which increases motivation of the patient to more actively participate in the rehabilitation process [15, 36, 83]. Another advantage of the VR rehabilitation is the ability to target a specific disability (e.g. training of grip strength). Many of the factors that

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[1] http://www.immersion.com

do not contribute to the functional improvements can be eliminated through selective visual representation. The training can be adjusted to the extent of patient's functional abilities while the visual representation displays performance in a larger scale. In this way patients can perform some of the tasks even with reduced functionality which may hinder them in everyday life. Performance of VR tasks with high level of presence also stimulates patient's emotional and cognitive experiences similar to those in real-life situations. The repeated task execution can initiate relearning process in the central nervous system to be able to reproduce complex cognitive and motor procedures as experienced during daily activities (e.g. motion planning, force control, obstacle avoidance, attention shift) [15].

One of the drawbacks of VR rehabilitation is that the contribution of such training to the overall outcome of the rehabilitation is difficult to evaluate [97]. An important question that arises is how much of VR rehabilitation should be given to a patient in addition to conventional physical or occupational therapy. Prolonged use of VR can result in *virtual reality sickness* with symptoms similar to motion sickness. The symptoms of VR sickness include temporary nausea, dizziness, headache, loss of balance, impaired vision and altered eye-hand coordination [42, 83]. Special care should be taken when applying VR rehabilitation to patients with sensory-motor disorders. Some patients may not be suitable for such training therefore preliminary testing is needed. The suggested duration of one training session is about 20-30 minutes [97]. With that in mind, the VR rehabilitation should be considered as complementary method to the existing and well established methods used in physical and occupational therapy.

Overall, the use of VR rehabilitation can reduce long-term costs of traditional rehabilitation by reducing the time and resources needed to treat a patient. Rehabilitation in virtual environment allows better safety of the patient, automated documentation and less time needed to set up the training equipment [42]. The tasks and exercises can be easily adjusted to individual's skills and abilities. Many of the VR exercises can also be performed by a patient at home using a desktop computer with an appropriate input device without the physical presence of a therapist. The progress of the rehabilitation can be followed by a physician or therapist through a network connection [92].

1.3 Methodology

In this research we first used the grip force tracking method as an assessment tool to evaluate grip force control in different functional grips of healthy subjects and patients with neuromuscular diseases. The method was further applied as a training modality with the aim to improve sensory-motor functions in persons following stroke. A novel grip-measuring device based on three-dimensional force transducer was designed to assess dynamic forces in different grips used in daily activities (e.g. pinch for writing with a pencil, cylindrical grip for drinking from a glass, lateral grip when using a spoon) [61]. The proposed measuring system allows exchange of different end-point objects to assess the grip force control in grips similar to those evaluated in hand function tests [33]. The force measuring unit was used as an input to a tracking task where the person had to apply the grip force according to the visual information from a computer screen. Tracking tasks have been used previously to study the development of grasping in human [4], to assess the coordination of grip force in patients with Parkinson's disease [111], as a therapy for hemiplegic patients [59] and to evaluate grip force control in patients with neuromuscular diseases [62].

We performed the assessment of the grip force control in different age groups of healthy subjects [63] and in a group of patients with neuromuscular diseases [62]. The method was also applied in a case study in a patient after head injury to evaluate the effects of botulinum toxin treatment [10, 95] to reduce spasticity of the hand and possibly improve the force control of the fingers [63]. The proposed grip force tracking system was further applied as a supplemental therapy to train hand function in patients after stroke.

In the second part of the thesis work, the original grip-measuring device was improved with the aim to provide more information on how the forces are being applied by individual fingers. The developed isometric finger device allows the measurement of fingertip forces and torques of the thumb, index and middle fingers during closing and opening of the hand. The finger device was used for multi-fingered grasping in a virtual environment. Several VR tasks were designed to simulate different functional activities that include grasping and manipulation of objects. Since the isometric device completely constrains the movement of the fingers, pseudo-haptic approach was used [65], where visual and tactile information provide feedback on the forces and dynamic behavior of objects in virtual environment. Mathematical model of multi-fingered grasping adopted from the analysis of robotic hands [84, 85] was implemented to determine the forces and torques affecting dynamic response of a virtual object. Based on the developed library for multi-fingered grasping and manipulation, four training tasks were programmed with the aim to improve grip force control and grip strength in patients after stroke or other conditions affecting sensory-motor function of upper extremity.

1.4 Thesis Original Contributions

The main goal of the dissertation was to develop a virtual reality based force assessment system which could be used for evaluation and rehabilitation of hand function. Several new assessment and rehabilitation methods based on measurement of grip force in virtual environment have been proposed. The following contributions of this work can be identified:

- design and realization of the grip force measuring device for the assessment of different functional grips
- development of the hand function evaluation method based on the force tracking task
- use of the tracking system for the assessment of grip force control in patients with neuromuscular diseases, evaluation of botulinum toxin therapy and rehabilitation of hand function in persons after stroke
- design and development of novel isometric finger device for the measurement of force in three-fingered grips
- design and realization of VR based assessment and rehabilitation system for training of hand function while using the pseudo-haptic approach for multi-fingered grasping and manipulation

2 Human Hand and Grasping

Human hand has the ability to adapt to many different tasks of everyday living. The biomechanical structure of the hand allows articulated manipulation of different objects, high dexterity, and tactile sensing. The main function of the hand is grasping. When the object is grasped, the posture of the fingers is selected based on the geometric properties of the object and the requirements and constraints of the task. For many assignments, people developed different tools that promote hand functionality, but the role of the hand in daily activities is irreplaceable. The loss of hand function due to an injury or disease can seriously affect a person's ability to perform everyday activities (e.g. feeding, grooming, writing). Different methods of rehabilitation and physical therapy are applied to help such people regain a certain degree of functionality. This chapter describes the biomechanical structure, muscular control and different properties of the human hand which are important for the evaluation of hand function in rehabilitation.

2.1 Human Hand

The human hand is one of the most complex biomechanical structures. The hand consists of 27 bones which are divided into three groups: 8 carpal bones in the wrist, 5 metacarpal bones forming the palm, and 14 phalanges of the fingers (Figure 2.1) [32]. The carpal bones consist of short bones which are joined close together, connecting the forearm and the palmar side of the hand. The five metacarpal bones are longer than the carpal bones and cylindrical in shape. They are connected to the carpal bones at their proximal side and to the proximal phalanges at their distal end. Each finger consists of three phalanges: proximal, medial and distal. The structure of the thumb differs from the structure of the other fingers. The thumb has a prolonged distal phalanx, while it is missing the middle phalanx. The metacarpal bone of the thumb is separated from the rest of the metacarpal bones allowing much higher freedom of movement.

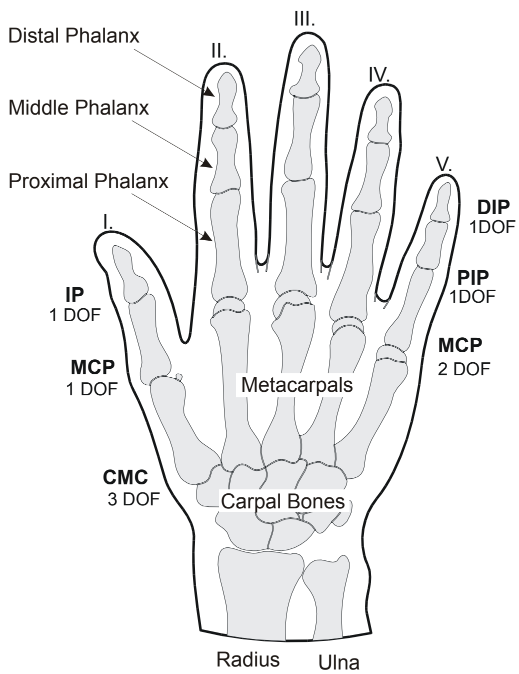

Figure 2.1: Biomechanical structure of the hand.

The human hand has between 25 and 28 degrees of freedom (DOF) [45]. The anatomical structure of the hand allows high dexterity during interaction with the environment and manipulation of objects. The proximal phalanx of the thumb is linked to the carpal bones of the wrist through carpometacarpal (CMC) joint which has three degrees of freedom (3 DOF), providing flexion-extension, adduction-abduction and internal-external rotation (Figure 2.2). The middle metacarpophalangeal (MCP) and distal interphalangeal (IP) joints have each one degree of freedom (1 DOF) allowing flexion-extension of the thumb. The metacarpophalangeal (MCP) joint of the four fingers has two degrees of freedom (2 DOF) permitting flexion-extension and adduction-abduction. The proximal interphalangeal (PIP) joints and distal interphalangeal (DIP) joints have each one degree of freedom (1 DOF) allowing only flexion-extension.

The movement of the hand is controlled by 34 muscles which consist of *extrinsic* and *intrinsic* muscles. The extrinsic muscles originate in the forearm, while the intrinsic muscles are located mainly inside the hand. The first group of muscles is used when performing gross movements and tasks with high strength requirements. The extrinsic muscles activate the movement through a system of tendons connecting each muscle with the corresponding bone segments. The intrinsic muscle group provides accurate finger movement and precise force coordination between the fingers. Several muscles are simultaneously activated during hand reshaping or finger movement. The muscles contributing to the movement represent the *agonistic* muscle group and muscles opposing the movement form the *antagonistic* muscle group. The third group of muscles consists of *synergistic* muscles which stabilize and balance the movement and contribute to the grip strength [102].

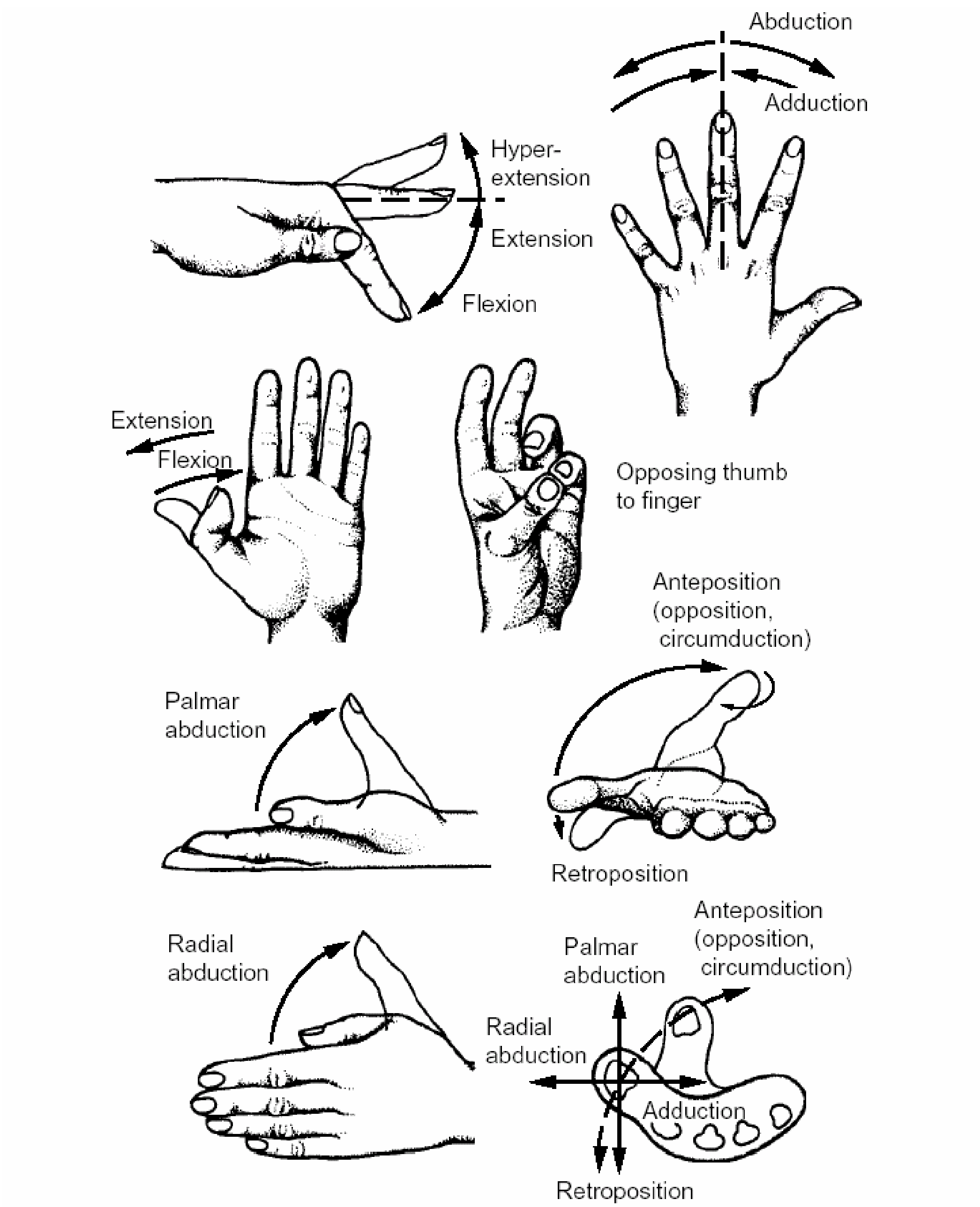

Figure 2.2: Different types of finger movements which are employed during grasping and manipulation of objects (adapted from [105]).

When the fingers are flexed, the flexion is first initiated in the distal joints followed by the flexion in the middle and proximal joints. Due to the complex muscular structure, the motion of finger segments is coupled. The thumb has the highest degree of independence actuated by eight muscles. Three degrees of freedom in CMC joint, which include flexion, abduction and medial rotation, allow repositioning of the thumb to oppose any of the fingers (Figure 2.2). The opposition of the thumb has an important role during grasping and manipulation of objects allowing precise control of the fingertip forces [86]. The loss of one's thumb or reduced ability to control its movement can decrease the functionality of the hand by 40% [50]. The finger with the next highest degree of movement independence is the little finger. When an object is held in a power grip, the little finger is oriented towards the thumb to provide additional stability. The loss of the little finger represents much greater impairment than the loss of the second, third or fourth finger [19].

The human hand is covered with skin which provides protection and firm support during grasping and interaction with different objects and surfaces. Rugged surface of the skin, covered with numerous crests, increases the friction between the hand and grasped surface. Sweat glands located inside the skin make the surface of the skin moist, affecting in this way the friction coefficient between the skin and the object surface. The high friction at the contact provides better stability and prevents the object to slip out of the grip [71].

2.2 Sensory-Motor Control

Finger movement is controlled by the central nervous system (CNS) which regulates hand and arm muscles to act in synergy. The motor control of movement and posture is organized hierarchically [94]. The central nervous system receives feedback from numerous body receptors providing information on the location of the object, position of the fingers and applied force. In terms of control theory, such a biological system can be described as a closed-loop system with multiple inputs and outputs (Figure 2.3). Different parts of the brain are activated during a grasping task. Visual information is primarily processed in the occipital lobes. Sensory information from the receptors located in the skin, muscles and joints is processed in the parietal lobes. Based on the afferent information, voluntary motor activity is controlled by the frontal lobes of the brain [57]. The more automated behavior (e.g. reflex) is controlled at the level of the spinal cord or brainstem. To initiate movement of a finger, the motor cortex sends nerve impulses through the spinal cord. The nerve impulses are distributed either directly to motor neurons inside the muscle fibers or indirectly through inter-neurons. The inter-neurons coordinate many of the motor actions including reflex motor responses. The motor commands simultaneously activate motor neurons innervating agonistic muscles and inter-neurons inhibiting the agonistic muscles [94]. Each motor neuron, innervating between 10 to several hundred muscle fibers, defines one motor unit [32]. Based on the functional characteristics three types of motor units exist: *slow twitch fibers* (i.e. type I) with low force and low fatigue factor, *fast twitch fibers* (i.e. type IIa) which are large and exert high forces but fatigue faster, and *fatigue-resistant fibers* (i.e. type IIb) which exert moderate forces with low fatigue. When a muscle is activated, several motor units of different types are activated simultaneously depending on the requirements of the task. Muscle contraction can be *isometric* where the muscle length remains unchanged, *concentric* if the muscle is shortening and *eccentric* if the muscle is lengthening. During grasping and manipulation isometric contraction is activated when the object is securely grasped and the finger forces are adapting to compensate any external forces.

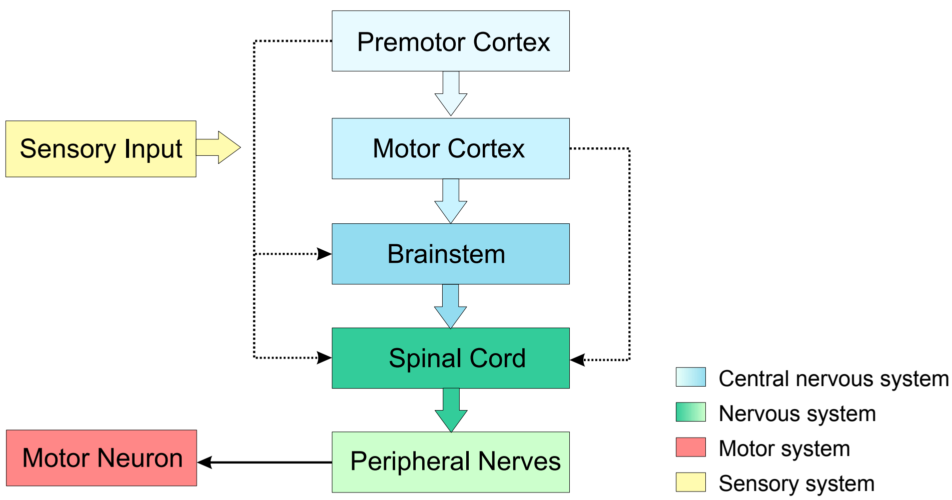

Figure 2.3: Motor control loop for voluntary activation of muscles.

2.3 Grasping

Grasping is defined as the application of functionally effective force of the hand to an object to accomplish a task within given constraints [71]. The term *grasp* defines dynamic unfolding of a hand posture and the term *grip* denotes a static hand posture. When an object is grasped, the fingers have to apply forces that satisfy functional constraints of the task (e.g. compensate gravity, resist external force) and physical constraints of the object (e.g. shape, weight, friction) [86]. The key goal in most grasping tasks is to maintain a stable grip by adapting the contact forces of the fingers and the hand. Accurate grip force control is essential in performing activities such as grasping of fragile objects, resistance to external forces (e.g. holding a spoon to resist gravity), and when applying movement to an object (e.g. turning a knob). The stability of a grip greatly depends on the selected hand posture. Functional demands on the posture include: application of force to match anticipated force of the task, application of motion to the object to change its position or orientation, and gathering sensory information to learn more about the object or the environment. Various hand postures allow different degrees of available force, motion and sensory information [45]. Different grip types can be identified when performing daily activities. Several grip classifications have been proposed for the purpose of biomechanical analysis and hand functionality evaluation [45, 86, 20].

Napier [86] considered functional properties of the task and divided grips in *precision* and *power grips*. When the emphasis of the task is on strength and stability of the object, power grips are used (e.g. holding a hammer). The object is grasped between the fingers and palm to achieve high stability. The contact surface between the object and the hand is large enough to prevent slippage. Precision grips are used when high dexterity and manipulability of the grasped object is required (e.g. grasping a pencil). In precision grip the object is grasped between the tips of the thumb and the opposing fingers, providing high compliance and tactile feedback during manipulation.

Additional functional properties can be observed from the classification in *opposition space* [45]. The term *opposition* describes three basic directions in which the human hand can apply forces. The three opposition types are: (1) pad opposition, (2) palm opposition, and (3) side opposition. Pad opposition occurs when the object is grasped between the tips of the thumb and fingers. Due to a large concentration of tactile receptors at the finger pads, such grips have high compliance between the object surface and fingertips and consequently provide high coordination of force (e.g. grasping of small objects). In palm opposition the object is grasped between the fingers and the palm providing additional stability when applying higher grip forces (e.g. grasping a full glass of water). Side opposition occurs between the hand surfaces along a direction transverse to the palm. The object is positioned between two adjoining fingers or between the thumb and lateral side of the index finger. Side opposition combines power and precision, providing good stability of the object with relatively high dexterity.

Selection of a grip is often based on the geometric properties of the object being grasped. Figure 2.4 shows the classification proposed by Schleisinger (1919) where six different hand postures were identified: pinch grip for small objects, cylindrical grip for long and cylindrical objects, spherical grip for spherical objects, lateral grip for flat objects, three-jaw chuck for small cylindrical objects and hook grip for lifting or pulling

[19]. It is estimated that in about 40% of daily activities which involve grasping or manipulation of objects tip pinch and lateral grip are used [79].

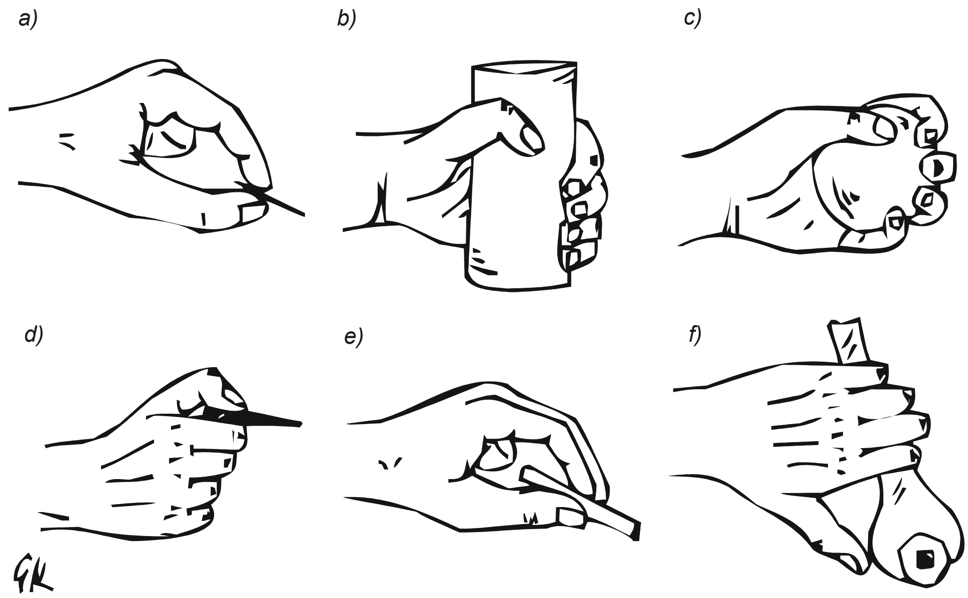

Figure 2.4: Classification of grips used in daily activities as proposed by Schleisinger (a – tip pinch, b – cylindrical grip, c – spherical grip, d – lateral grip, e – three jaw chuck, f – hook grip).

The maximal force which can be applied by the hand depends on several factors such as grip type [22], geometric properties of the object [2], posture of the arm and body [54], gender, age [89], anthropometric parameters [24], hand dominancy, and different environmental factors [101]. In precision grips, where the object is manipulated with high compliance, the maximal forces are in the range of 40 N to 100 N (Table 2.1). The maximal forces in power grips can be about five times higher. It has been estimated that the maximal grip forces required to perform about 90% of daily activities are in the range up to 40 N [50]. Table 2.1 shows the maximal grip and pinch forces in the dominant hand as assessed in male and female subjects. The maximal exerted force depends on type and length of muscles used to perform the grip. Power grips mainly employ extrinsic muscles of the forearm when activating the movement. The force is transferred through tendons which are lead over several joints. The body posture can therefore greatly influence the maximal available force. The highest grip force is exerted with 0˚ of abduction in the shoulder, 135˚ of flexion in the elbow and neutral wrist position [54]. If the arm is repositioned, the maximal grip force can be reduced for about 40%.

Table 2.1: Average maximal grip force in the most frequently used grips for male and female subjects [24]:

Average Grip Force (N)	*Male* (n=50)	*Female* (n=50)
Lateral Grip	97.02 (28.52)	64.84 (27.02)
Tip Pinch	62.88 (30.54)	45.45 (30.59)
Three-Jaw Chuck	95.37 (29.63)	64.13 (31.10)
Power Grip	452.44 (22.75)	288.91 (21.23)

An important property of the human hand is the accurate perception of movement, position and force. Sensory receptors located in the muscles, skin and joints provide feedback information on the position of the fingers to the central nervous system. A person is capable to distinguish changes of the finger position with the sensitivity of about 1˚ and joint movement velocity faster than 4˚ per minute. Proprioceptive sensing is important when gathering sensory information during interaction with the environment. Humans can discriminate the change of a plate thickness for 0.075 mm. Another important factor for object manipulation is tactile sensing of the applied fingertip force and other parts of the hand. Haptic discrimination of force depends on the level of the applied force. The relative change of grip force that a subject can still discriminate is about 7-10% over the range of 0.5 N to 200 N and 15-27% when the force is below 0.5 N [50].

3 Evaluation and Rehabilitation of Hand Function

Hand function can be greatly reduced due to hand injury, neurological or neuromuscular disease, central nervous system trauma or stroke. Different treatment and rehabilitation methods are applied to restore hand function. Diagnosis of disease or injury affecting the hand includes measurement of the maximal grip force, range of motion, assessment of dexterity, and evaluation of sensitivity to contact, vibrations and temperature [79]. Several hand function tests are in clinical use to quantitatively or qualitatively assess the performance of every day activities that involve grasping and manipulation of objects. The majority of the evaluation and measurements is still performed manually and often lacks objectivity and sensitivity needed to detect small changes in performance. The use of standardized methods and computer-assisted measurements can increase the accuracy, repeatability and objectivity of the assessment while reducing the time needed to perform the evaluation [18]. In this chapter we discuss grip force assessment in clinical practice and present some of the research work performed in the area of grip force measurements.

The restoration of hand function is achieved with different methods of rehabilitation. The rehabilitation consists of repeated training with the emphasis on tasks used in daily activities, such as picking up small objects, manipulating objects of various shapes, use of different tools and others. Rehabilitation methods vary depending on type and level of disability affecting the hand function. The focus of the second part of this chapter is mainly on the rehabilitation after CNS injury where the sensory and motor functions can be both affected. Previous studies have shown that the feedback information associated with the performance of a motor task can assist the rehabilitation process. Use of virtual reality for feedback offers flexible and visually attractive environment for training while motivating the patient to improve with each training session. Some of the existing research in VR rehabilitation of the hand is also presented in this chapter. Finally, a general rehabilitation scheme for the computer assisted assessment and rehabilitation is proposed.

3.1 Evaluation of Hand Functionality

Hand functionality is defined as the level of the functional ability to grasp and manipulate different objects (e.g. grasping a glass of water for drinking, grasping and turning the key to open the door, grasping and holding a pencil to write) [79]. The information on hand functionality is often obtained indirectly by assessing the motion range of the fingers and wrist, grip strength and hand dexterity [73]. The variability of such measurements can be relatively large limiting in this way detection of small changes following therapy or progress of a disease [18].

The grip strength measurements are mainly focused on the assessment of the maximal voluntary grip force that provides information on short-duration muscle strength rather than the functional force [90, 102]. Most daily activities that involve grasping and manipulation of different objects require sub-maximal forces [50], therefore the assessment of the maximal voluntary grip force reflects only a partial information on hand functionality [79, 112]. The grip strength is usually assessed using different mechanical dynamometers that measure the level of the applied grip force but no information is obtained on the dynamics and direction of the force [47]. Capturing the grip force vector (i.e. grip strength and direction of the force) in a time frame can give additional knowledge on how the grip is applied to the object [39, 61, 112, 114]. The dynamometers used are often not suitable for accurate measurements of low-level forces (e.g. typical in patients with neuromuscular diseases) because their measurement range is too large with respect to the force applied [18, 47]. The assessment can be improved by introducing electronic dynamometers that allow real-time measurements of the grip force providing the clinician with a force-time curve [53]. The force-time curves can be examined for deficits in the grip force control in patients with affected sensory-motor functions [39, 60]. The second drawback of the dynamometers used in clinical practice is the shape of the measuring handle which differs from objects used in daily activities. Instrumented objects have been proposed to assess the functional grip forces applied on objects which are in shape and size similar to the objects used in daily activities [16, 31, 61, 77, 80].

Different factors influencing the hand function are often closely related. Grasping and manipulation tasks involve motion, strength, dexterity, and motivation. A patient with adequate strength may not be able to perform a simple task due to an insufficient force coordination and poor range of motion. A different patient may face the opposite problem with sufficient range of motion but insufficient strength or sensory-motor control to grasp the object. Hand functionality also depends on the ability to perform different grips. However, static description of the hand alone does not provide sufficient information to describe patient's functional state [79]. In contrast to indirect measurements of different biomechanical parameters, several tests consisting of tasks similar to daily activities have been proposed to assess patient's hand functionality. The existing hand function tests include manipulation of different objects where the performance of tasks is evaluated either by measuring the time required to perform the task or by descriptive or semi-quantitative assessment made by a physical therapist. Hand function tests include: Activities of Daily Living (ADL) tests [79], Jebsen Hand Function Test [49], upper extremity part of the Fugl-Meyer Motor Test [33], Manual Muscle Test (MMT) [35], Smith Hand Function Test [103], Nine Hole Peg Test of finger dexterity and others.

Jebsen Hand Function Test is among the most commonly used tests in rehabilitation. The test includes seven tasks (e.g. feeding, writing, turning pages, grasping and transporting large and small object) which a patient has to perform as fast as possible. The scoring of the performance is based on the time needed to complete each task. Reference data of healthy subjects ranging in age from 20 to 94 years are available for males and females [49]. The drawback of Jebsen Hand Function Test is that the test only evaluates rate of performance but no importance is given to the qualitative aspects of performance (e.g. body posture during the assessment, hand posture). The results of individual subjects may vary significantly and since no data is usually available prior to the onset of patient's condition, the result of the test may not reflect absolute level of disability.

In patients with affected sensory-motor functions, such as stroke patients, Fugl-Meyer Motor Test is often applied to assess the level of disability or to follow the progress of recovery [33]. The test evaluates full body motor functions, range of motion and sensation properties. The upper extremity part of the Fugl-Meyer test includes evaluation of five different grips (e.g. hook, lateral, pinch, cylindrical, and spherical grip) which require co-activation of several muscles. The grips are performed on standardized objects (e.g. tennis ball, sheet of paper or cardboard, small soda cup). The patient is instructed to maintain the grip against relatively high external force while the examiner tries to pull the object out of the patient's grip. The performance is numerically scored, with "0" if the required position cannot be acquired, with "1" if the grip is weak and with "2" if the grip can be maintained against resistance. Flexion and extension of the fingers are also assessed in a similar way. During testing patient's arm is supported at the elbow, which is kept at 90° of flexion, while the wrist remains unsupported. The Fugl-Meyer method is considered to have high reliability for the clinical assessment of function and comparative analysis of the effects of various therapeutic interventions [26].

The major issue of hand function tests is the objectivity of the methods which depend on the experience of the examiner [79]. Some of the function tests [49, 103] evaluate the upper extremity as a whole without separating the arm and the hand. The detection of changes in hand function and finger dexterity is in that way limited. The accuracy and objectivity of hand function evaluation can be increased by introducing simple quantitative methods based on accurate and sensitive assessment and measurements of different parameters, such as functional force [16, 35, 38, 89], grip force control [18, 53, 62], posture of the hand [25, 116], position and velocity of the object grasped [80], contact distribution of the hand [13, 29] and others.

3.2 Rehabilitation of Hand Function

Hand rehabilitation is aimed to restore and maximize hand function while avoiding injury. Different methods of rehabilitation and therapy are applied to achieve this goal. Conventional rehabilitation practice consists of *physical* and *occupational* therapy given to a patient after the initial treatment. In general the physical therapy is aimed to enhance patient's endurance and functional abilities, improve muscle tone, increase muscular strength, enhance range of motion of the fingers and wrist, improve coordination of movement and enhance grasping capabilities. In physical therapy patients are trained to use different prosthetic devices, orthoses, and splints needed to return contracted muscles to a relaxed position. Physical therapists also assist and provide instructions to patients on home exercise programs.

Occupational therapy is aimed to reduce the effects of an injury or condition, prevent further disability and help to relearn the activities of daily living (ADL's), such as eating, bathing, dressing, homemaking and personal hygiene. Occupational therapists also teach patients how to use different assistive devices and techniques to help them improve functioning in daily living tasks [104].

Repetitive training of isolated movements (e.g. isotonic or isometric activation of muscles) can improve the outcome of motor rehabilitation while increasing muscle tone, grip strength and dexterity [12]. Functional electrical stimulation can be also applied to train hand function and to restore some of the grasping capabilities in patients after central nervous or spinal cord injury [1, 88, 93].

Process of rehabilitation should be followed by assessment of hand function on a regular basis in order to evaluate the effects of the applied therapy. Accurate and objective assessment can help select the optimal therapy and reduce the time needed for rehabilitation. Computer assisted rehabilitation under the supervision of a therapist can incorporate the assessment and the training function. The performance of the tasks is automatically scored and the results can be used to adjust the therapy to patient's abilities to always maximize the performance. The performance during the training can be assessed by different measuring systems such as a force measuring unit [59, 63, 70], data gloves [116] or electro-optical measuring systems [61]. In case of injury or finger paralysis, the exercise of the finger movement can be also assisted by miniature rehabilitation robots with haptic feedback [48, 72].

3.3 Rehabilitation after Stroke

Stroke occurs due to an abnormal blood flow inside the brain which can be affected either when the vessel clogs within and interrupts the blood flow (*ischemic stroke*) or when the vessel inside the brain ruptures causing the leakage of blood into the brain tissue (*hemorrhagic stroke*). Ischemic stroke is the most common stroke and it occurs in about 83% of all cases. The stroke usually affects only one side of the brain. The amount of disability depends on the area of the brain where the stroke occurred. The survival rate of people affected with stroke is about 79% [87].

Due to the complexity of the central nervous system injuries and the number of new patients every year, the therapy of stroke survivors represents one of the most challenging tasks in rehabilitation [40]. The majority of post-stroke patients have initial weakness or paralysis of the arm and leg on one side of the body. After stroke the muscle control and muscular strength of the upper extremities can be affected and the ability to perform different activities of daily living is greatly decreased [33]. Four different stages of stroke can be identified: *prevention*, *acute phase*, *recovery phase* and *phase of long-term adjustment* [40]. The two important stages for the rehabilitation of hand function (and other body functions) are the last two. The majority of improvements occur in the recovery phase during the first 12 weeks after stroke. Additional recovery is expected in the phase of long-term adjustment, within the first 3 months after stroke, when also the intensity of the physical therapy should be increased. Some post stroke recovery (5-10%) can still occur between 6 months to 1 year after stroke. During this phase different rehabilitation programs are applied to restore patient’s hand function. The evaluation and rehabilitation of the hand is focused on restoring the affected sensory-motor functions through repetitive functional training [93]. The rehabilitation should include intensive training of different muscle groups for early recovery of the sensory-motor system and to possibly achieve the long-term effects [99].

In patients after stroke the ability to control and scale grip forces is greatly reduced [28, 39]. Restoration of the grip strength and force control is therefore an important assessment score of upper limb recovery [6]. The therapy in stroke patients should include (1) training of sensory-motor functions, (2) training of cognitive functions, and (3) training of skills needed to perform daily activities [104]. Motor rehabilitation consists of repetitive hand and finger movements through functional activity. Performance can be also improved by constraint induced movement therapy [70] where the less-affected limb is restrained while the affected limb is lead through different exercises which can include target tracing and tracking tasks. The repetition of different motor tasks can initiate the relearning process inside the central nervous system and contribute to the functional improvements of the affected muscles [40, 94, 109]. The rehabilitation can be enhanced by introducing cognitive feedback to the patient. The cognitive feedback can be presented in the form of video or audio information or tactile stimulation, either after each training session or in real time during the therapy.

In many stroke patients spasticity of the muscles can occur. Spasticity is a result of an incorrect reorganization of the CNS after a lesion, resulting in increased muscle tone, increased tendon reflexes, altered reflexes, loss of voluntary motor control, increased weakness, muscle fatigue, and lack of dexterity. Spasticity can be reduced through different methods of therapy such as physical therapy, drug treatment, botulinum toxin treatment, use of electrical stimulation, and orthopedic treatment [46].

3.4 Rehabilitation in Virtual Environment

Rehabilitation in VR allows enhanced learning through augmented feedback by means of a controlled training environment. Previous studies have shown beneficial effect on the hand function when performing different task in a virtual environment [11, 17, 42, 43, 48, 106]. The VR rehabilitation of the hand allows isolated training of specific functional parameters such as range of motion, strength, speed and accuracy of finger movement, grip force coordination, and dexterity. Several systems for VR based hand rehabilitation have been proposed but the number of clinical reports is limited. Merians and colleagues [81] presented a case study in three patients after stroke who trained with CyberGlove and Rutgers Master II-ND haptic system [9]. The patients were required to perform different VR tasks such as peg-board task and reach-to-grasp tasks. They participated in a three-week intensive training with the aim to increase their range of motion, speed of movement and strength. Similar study was presented by Jack and colleagues [48] who used the same VR based rehabilitation system to evaluate the training with functional clinical outcome measures. Three patients trained with four different tasks to exercise specific parameters of hand function: range, speed, coordination of fingertip force and strength. The subjects were tested before and after the training using Jebsen and Fugl-Meyer motor tests. After 10 days of training, all three patients showed significant increase in dexterity and strength.

Holden and Dyar [42] applied VR training to a group of 9 patients after stroke. The patients used CyberGlove and a magnetic tracking system to measure the position of the hand. The VR tasks were aimed to enhance dexterity of the hand and improve arm movement. The patient had to insert several different objects into a virtual torus while holding a real object, which corresponded by shape to the virtual object on screen. The target trajectory of the movement path was shown to the patient during the task. No haptic feedback was provided. The difficulty of the tasks was automatically increased or decreased after each trial based on patient's performance. The patients completed between 10 to 20 sessions incorporating several different movement patterns. The effectiveness of the VR training was evaluated by the upper extremity part of the Fugl-Meyer test and the Wolf Motor Test. Eight out of ten patients have demonstrated improvements on the clinical measures of the upper extremity function and strength.

Extensive research has also been performed in combined therapy of hand and arm using robot-aided rehabilitation in virtual environment. Rehabilitation robots, such as MIT-MANUS robot [58] and GENTLE/S rehabilitation system [69], allow different modes of therapy of the affected limb with full or partial robot assistance. The tasks are mainly aimed at performing different exercises with the upper limb or performing more complex activity, such as reach-to-grasp movements, however less emphasis is given to the restoration of the finger movement.

An important issue of any form of rehabilitation is the transfer of the therapy to real-life functional activities. The VR tasks can faithfully simulate different activities of daily living with the aim to restore hand function and improve dexterity (e.g. picking up objects in a virtual store [15]). On the other hand, the representation of the VR tasks can be more abstract and targeted to improve a specific capability such as movement coordination, grip strength, force control, and range of motion in a similar way as in physical therapy (e.g. inserting pegs into holes of different shapes [17]). Visually less complex tasks allow isolated training and assessment of specific hand function with reduced stress on the cognitive abilities. Such training could be applied in the earlier phase of recovery when the overall sensory-motor functions are still greatly reduced. The nature of VR allows gradual increase in the complexity of tasks and environments used for the therapy.

The participants in VR rehabilitation programs report greater enjoyment and improved confidence as compared to the patients enrolled only in conventional therapy [106]. The benefits of the VR training are difficult to evaluate in clinical practice. The performance of the tasks is influenced by several factors such as social, cultural, spontaneous stimuli, different neurological, cognitive and behavioral state before the rehabilitation, and many others [15]. The above reasons make it difficult from an ethical and practical point of view to produce an appropriate control group with no additional therapy because all patients should be entitled to all means of available therapy.

The progress of VR rehabilitation can be evaluated by a set of simple tests and assessment procedures within the virtual environment. We propose a scheme for VR rehabilitation consisting of two sets of tasks (Figure 3.1). VR tasks for training include more complex tasks which are focused on improving hand function and dexterity. The progress of training is followed by assessing parameters which reflect overall performance of the tasks, such as the time needed to complete a task or the number of successfully completed trials within a given time period. The training tasks can simulate different activities of daily living. The second block in the scheme represents a set of VR tasks for the assessment which are aimed to evaluate the effectiveness of the therapy through accurate and quantitative measures reflecting different functional parameters of the hand (e.g. range of motion, grip force control, grip strength). The tasks for the assessment should be simple in visual representation in order to minimize stress on patient's cognitive abilities. The training tasks should be performed daily while the assessment can be performed on a weekly basis.

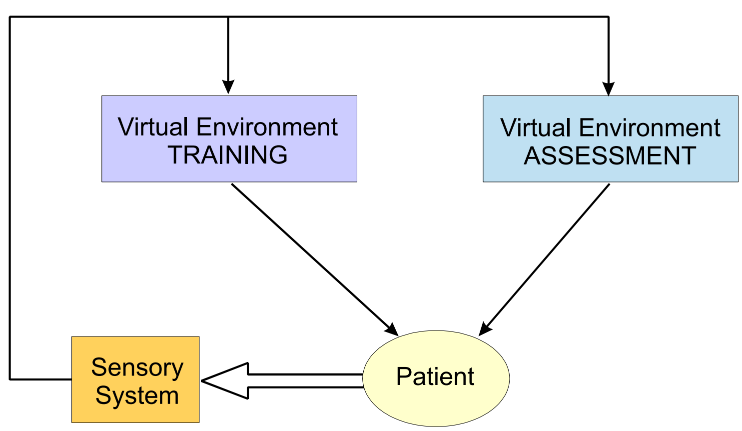

Figure 3.1: Rehabilitation in virtual reality consists of a set of tasks for the training and a set of tasks for the assessment. The sensory system measures patient's motor response and provides input to the virtual environment.

3.5 Computer Assisted Rehabilitation System

The overall scheme of a computer assisted rehabilitation system intended for the assessment and restoration of grasping is presented in Figure 3.2. The system consists of three subsystems: sensory, actuation and cognitive feedback. The sensory subsystem includes the assessment of the characteristic parameters affecting hand functionality, such as finger mobility, grip force, grip geometry, hand aperture, finger joint torques, force control and others. Computerized assessment methods allow objective, accurate and time-efficient evaluation. The assessment can also provide important information for the development of actuation systems which promote patient's grasping and manipulation abilities.

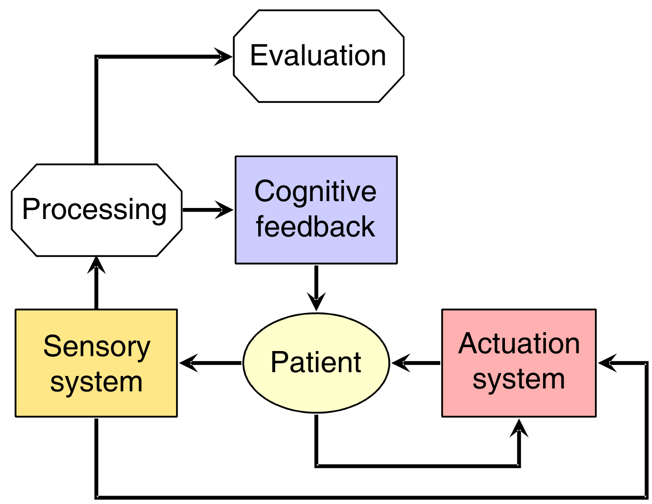

Figure 3.2: General scheme of a computer assisted rehabilitation. The sensory subsystem is used to assess several parameters of the hand, the actuation system represents different rehabilitation modalities (e.g. functional electrical stimulation, active hand orthoses, and rehabilitation robots) and the cognitive system provides feedback on the performance to the patient.

The actuation system includes functional electrical stimulation of hand muscles, active orthoses, haptic interfaces, and rehabilitation robots enabling therapy of finger and hand movements. The actuation subsystem provides full or partial support to the patient during the rehabilitation process. The control of the actuation system can either be pre-programmed, fully supervised by the patient or in the closed loop with the sensory subsystem. The third subsystem represents the cognitive feedback on patient's performance. The cognitive feedback can be presented to the patient in the form of video or audio information or sensory stimulation either after each session or in real time during the therapy to increase therapeutic influence on the rehabilitation process. The rehabilitation system can also include only the sensory and cognitive systems without any additional actuation. The training has to be adjusted to maximize patient's existing motor skills.

4 Assessment of Grip Force Control

Accurate force control is essential when performing activities such as grasping of fragile objects, resisting to external forces (e.g. lifting an object) or when applying movement to the grasped object [4, 45, 112]. Finger movement is controlled by the central nervous system which regulates the activity of the hand and arm muscles to act in synergy. The central nervous system receives dynamic feedback information from the visual sensors and from other exteroceptive and proprioceptive body sensors while regulating the motor output.

The development of sensory-motor functions shaping the hand skills begins in human at nursery age. Voluntary grasping develops at 4 months of age and the first precision grasping appears at the age of 10 months [30]. Grasping and manipulative skills further develop in subsequent years. The sensory and motor functions are enhanced during the childhood until they become fully developed [4]. Due to the aging process in adults, which affects the sensory and motor functions, the ability to control the grip force is gradually decreased affecting the performance of fine manipulation tasks. Control of hand muscles can be further affected due to the aging related neural diseases such as Parkinson's disease where the presence of tremor and reduced motor control result in irregular grip force patterns [60]. The grip force control can be also affected by different neural and neuromuscular diseases or injuries of the hand or the central nervous system (e.g. head trauma, stroke) [59].

Assessment of grip force control can provide important information on person's sensory-motor abilities affecting the hand function. Previous studies [18, 39, 53, 111] have shown the clinical importance of grip force control assessment. The studies suggest that the performance of visual-motor tasks is a sensitive indicator of sensory-motor disorders.

In this chapter we present a grip force tracking method for the assessment of grip force control. The assessment was first performed in a group of healthy subjects of different age groups to evaluate the influence of age and hand dominancy on the accuracy of tracking. A case study was performed in a patient after head-injury who was treated with botulinum toxin for hand spasticity to evaluate its influence on the force control [63]. In the last part of this chapter we present a study of the grip force control evaluation in patients with neuromuscular diseases [62].

4.1 Tracking tasks

Tracking tasks are visually guided motor task which require a person to track the presented target by movement of a limb or application of force [51, 115]. The movement or force output is typically presented on a computer screen simultaneously with the target. The target may be static or move in different directions. The tracking task can either be focused on *spatial accuracy*, where the accuracy in the position relatively to the target is emphasized (e.g. striking a small static target with a cursor), or on *temporal accuracy*, where the rate of tracking is important (e.g. following a moving target with a cursor). The task may incorporate spatial and temporal accuracy at the same time. The accuracy of tracking reflects the sensory-motor performance related to the observed motor activity. Tracking methods allow controlled assessment of the sensory-motor functions within the selected degree of freedom and given constraints on dynamic and amplitude range of the motor response. The visual representation can be simplified to reduce the stress on the visual perception (e.g. tracking of a square with a mouse cursor) or more complex to simulate real life situations (e.g. driving a wheelchair in a virtual environment). An important factor affecting performance is the time lag between the measured motor response and visual feedback. The time lag should be kept below 150 ms which is the minimum time interval needed for a person to process visual information [100].

The most frequently used type of tracking tasks are pursuit tracking tasks [51] where the target and output are simultaneously presented on the screen. Dynamic targets can move according to different signals such as sinus, ramp, step, rectangular or various randomized signals. The selection of the target signal depends on the purpose of the assessment. The sinus targets are aimed to assess performance during periodic motor activity, accuracy of tracking and endurance. The ramp targets are used to evaluate motor activity with a constant output rate. The rectangular targets are aimed to assess performance of ballistic movements, predictive behavior and temporal parameters of the sensory-motor system (e.g. response time). The tracking results can be analyzed in time or frequency domain. The accuracy of tracking is usually assessed by the *root mean square error* (*rmse*) between the target and the measured response. Other parameters include *correlation*, *index of coordination*, *phase lag* and *standard deviation of error* [51].

Figure 4.1 shows the basic scheme of the grip force tracking system used in our study [62, 63]. For the assessment of grip force control, the patient is presented with a target signal and the measured response on a computer screen. The target signal is shown in blue color and the force response in red color. Vertical position of a blue ring, located in the center of the screen, corresponds to the current value of the target and the position of a red spot corresponds to the applied grip force in real-time. The red spot moves upwards when the force is applied and returns to its initial position when the grip is released. The aim of the tracking task is to track the target as accurately as possible by adapting the force on the grip-measuring device. The grip force control is evaluated by comparing the target and response signals by different methods of signal analysis.

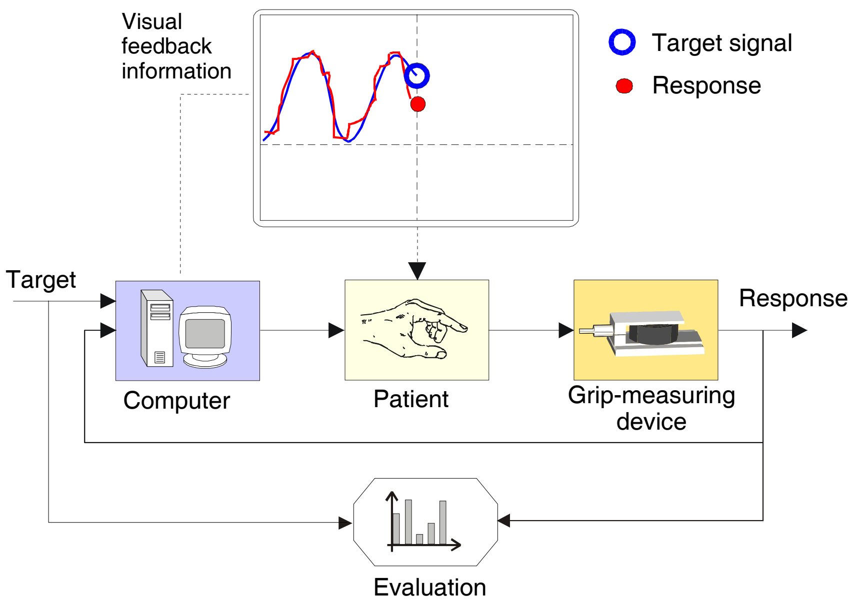

Figure 4.1: The block scheme of the grip-force tracking system used for the assessment of grip force control. The aim of the task is to track the target as accurately as possible by applying the appropriate force to the grip-measuring device.

4.2 Grip Force Measuring System

For the first concept of the tracking system we designed a grip-measuring device aimed to measure the force in different grips which are also evaluated in the upper extremity part of the Fugl-Meyer Motor Test [33]. The physical size and the shape of the attachments used were based on the standardized objects from the clinical test (e.g. tennis ball, small can, thin plate, and pencil). The instrument consists of the force transducer JR3 (JR3, Inc., Woodland, CA, USA) capable of measuring three-dimensional forces, several exchangeable end-objects and aluminum construction which allows the transfer of the grip force from the object to the sensor. The force measurement range of the sensor is 110 N in the *x*- and *y*-directions and 220 N in the *z*-direction, with the non-linearity of about 1% across the range [61].

The grip-measuring device can be fitted with different end-objects (Figure 4.2), such as ball, pencil, plate and cylinder, to assess the forces in different grips used in daily activities. The objects are made of two symmetrical halves that shape into a full object when attached to the device. The object in the shape of a pencil has the diameter of 10 mm at the distal end and the length of 28 mm. The object representing a thin plate has the contact area of 18 x 35 mm^2 and thickness of 5 mm. The object in the shape of a ball has the diameter of 70 mm. The cylinder represents a small can with the diameter of 55 mm and the length of 110 mm.

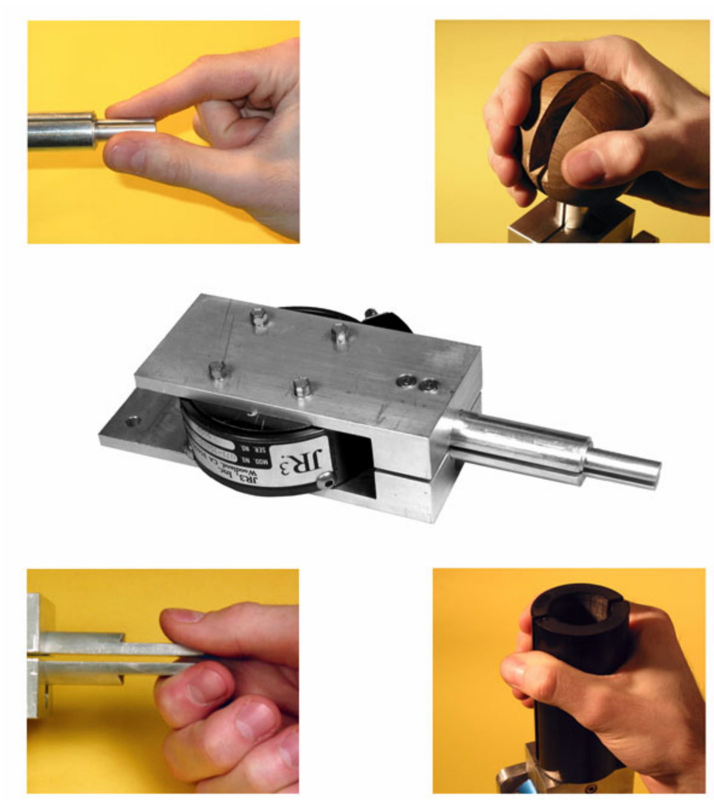

Figure 4.2: A grip-measuring device with different end-objects was designed to assess forces in grips used in daily activities (e.g. nippers pinch, spherical, lateral and cylindrical grip).

To achieve accurate measurement of the grip force, the sensor was calibrated by placing different weights at the center of the sensor and at the distal end of the device to correct the calibration matrix. The device was connected to a personal computer equipped with the 12-bit data acquisition card PCI-DAS1002 (Measurement Computing, Middleboro, MA, USA). The acquisition of the grip force was performed with the sampling frequency of 100 Hz. The grip-measuring device was calibrated to measure forces up to 100 N. The resolution of the measured force was 0.01 N in the measuring range of 0-25 N, 0.03 N in the range of 25-50 N and about 0.05 N in the range of 50-100 N. The output signal was filtered in real time with the 2nd order Butterworth filter (cut-off frequency 15 Hz).

4.3 Analysis of Tracking Results

4.3.1 Tracking Error

The accuracy of tracking was evaluated by calculating the relative root mean square error (*rrmse*) between the target $F_T(t)$ and the measured output force $F_O(t)$ over the trial time T:

$$rrmse = \sqrt{\frac{1}{T}\sum_{t=t_0}^{T+t_0}\frac{(F_0(t)-F_T(t))^2}{\max(F_T)^2}} \qquad (4.1.)$$

The tracking error was normalized by the peak value of the target to allow the comparison of the results obtained in different levels of force. A lower tracking error suggests better activation control of the muscles needed to maintain or adapt the grip force according to the target and consequently represents more enhanced hand functionality [4, 51].

4.3.2 Grip Force Coordination

The dynamic characteristics of the grip force can be assessed by analyzing the coordination of tracking. The coordination of tracking is described by the measured force $F_O(t)$ and the corresponding time derivative (i.e. force time-rate) dF_O/dt [51]. The obtained trajectory is plotted in the force-velocity domain, where the x-axis represents the force and the y-axis the force derivative. Normal grip force response to the sinusoidal target will result in a smooth circular trajectory in the force-velocity domain. Producing non-smooth response during the tracking of a sinusoidal target due to reduced muscle control will show as a non-circular plot. To assess spatial and temporal characteristics of performance, we quantified the grip force coordination by the correlation of the target signal and force response and the correlation of the corresponding time-rates using Pearson correlation coefficients. The coefficient of coordination (K_c) is defined as the product of the two correlation coefficients, where the value closer to one suggests more enhanced coordination of the grip force:

$$K_C = corrcoeff(F_O, F_T) \cdot corrcoeff(\frac{dF_O}{dt}, \frac{dF_T}{dt}) \tag{4.2}$$

4.3.3 Statistical Analysis

We calculated mean values and standard deviation to analyze the average performance in several trials or persons. The variability of the results between different groups was tested using one-way analysis of variance (ANOVA) for group samples and t-test to analyze relations between two groups. We considered p-values of 0.05 or less as statistically significant. The data were analyzed with Matlab software (The MathWorks, Inc., MA, USA) while the statistical analysis of the results was performed with SPSS software (Lead Technologies, Inc., Chicago, IL, USA).

4.4 Grip Force Control in Healthy Subjects

The aim of assessing the grip force control in healthy subjects was to investigate the differences among the subjects of different age groups. Other studies [4, 5] have only examined the force control of constant or slowly increasing targets but no other targets were analyzed. The focus of our investigation was the study of the grip force control when tracking dynamic targets (e.g. sinus) which require dynamic application of isometric force. The subjects included in-school children, young adults and older adults to provide a small control group for the assessment of grip force control in people with sensory-motor disabilities (e.g. neuromuscular diseases, stroke). We analyzed the influence of age and hand dominancy on the grip force control of the lateral grip. The influence of other grip types was evaluated only in the group of young adult subjects and the results are discussed in the study of grip force control in patients with neuromuscular disease (see the next chapter).

4.4.1 Subjects

The analysis of the grip force control was performed for three different age groups. The group of children consisted of 12 healthy children (C1-C12; mean age: 10 (SD 0.4) years), 4 of them were female and 8 were male (Table 4.1). Previous studies reported no influence of gender on the performance of tracking tasks, therefore the group of children was mixed [5]. The group of young adults consisted of 10 healthy male volunteers (S1-S10; mean age: 27.7 (SD 3.5) years) (Table 4.2). The group of older adults consisted of 10 healthy male volunteers (T1-T10; mean age: 55.6 (SD 3.1) years) (Table 4.3). All the subjects were right-handed.

Table 4.1: Data of the children

Subject	*Gender*	*Age*	*Subject*	*Gender*	*Age*
C1	M	10	C7	F	10
C2	F	9	C8	M	10
C3	M	10	C9	F	10
C4	F	10	C10	M	10
C5	M	10	C11	M	10
C6	M	11	C12	M	10

Table 4.2: Data of the young adult subjects

Subject	*Gender*	*Age*	*Subject*	*Gender*	*Age*
S1	M	27	S6	M	27
S2	M	25	S7	M	26
S3	M	28	S8	M	35
S4	M	28	S9	M	27
S5	M	30	S10	M	25

Table 4.3: Data of the older adult subjects

Subject	*Gender*	*Age*	*Subject*	*Gender*	*Age*
T1	M	55	T6	M	55
T2	M	62	T7	M	56
T3	M	54	T8	M	52
T4	M	52	T9	M	55
T5	M	56	T10	M	59

4.4.2 Methods

The grip force control was evaluated while tracking three different targets: ramp, sinus and rectangular target. During the test the subject was seated in front of the computer screen on a chair with adjustable height. The grip-measuring device was positioned at the edge of the table in the proximity of the subject's hand. The subject was asked to maintain the elbow in about 90° flexion and to keep the wrist and shoulder in a neutral position. Each subject was first explained the three tracking tasks and performed one test trial of each task. For the assessment one trial with the ramp, three trials with the sinus and one trial with the rectangular target were recorded. The ramp target increased during the interval from 2 to 17 seconds from the level of 0 N to 30 N for children, 60 N for young adults and 40 N for the older adult subjects. The sinus target had the frequency of 0.2 Hz and the peak force was set at 9 N for the children, 18 N for the young adults and 12 N for the older subjects. The peak forces were set at about 10% of the average maximal grip force in the lateral grip [75, 76]. The peak target forces for the rectangular signal were the same as for the sinus and the time period was set at 5 seconds. The duration of the tracking task was 32 seconds where the first two seconds of the trial, used for establishing the initial force level, were discarded from the analysis. The assessment was performed for the dominant and non-dominant hand. The total examination time was under 20 minutes per subject to minimize fatigue and loss of concentration. The tracking tasks were performed in random order to avoid learning effects.

4.4.3 Results

Figure 4.3 shows the average output signals with standard deviation as assessed in the three age groups when performing the ramp task with non-dominant and dominant hand. The results show considerably larger variability in tracking accuracy in the group of children as compared to the two adult groups. The average response in children shows slight undershooting of the ramp target. During the constant phase of the signal, the variability of the output force increased. Slightly larger variability was present when performing the task with the non-dominant hand. The adult subjects produced a smooth response with only small deviations and showed no significant influence of hand dominancy. Figure 4.4 shows the average tracking error during the linear increase and constant phase of the ramp signal. The children demonstrated the largest difference in accuracy between the two phases. The young adults performed both segments with similar accuracy, while the older adults show slightly larger deviations during increasing phase.

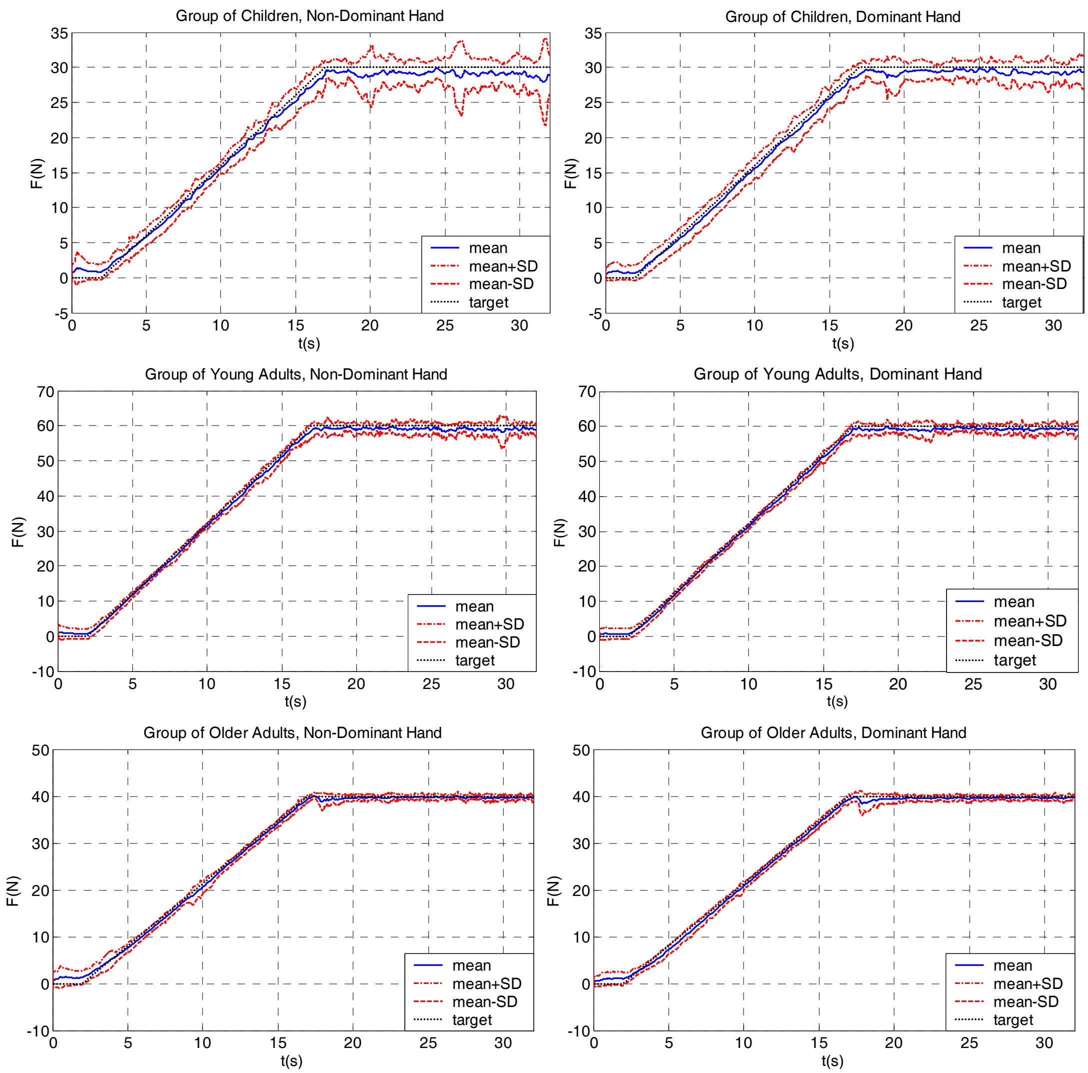

Figure 4.3: Average tracking outputs for the three age groups as obtained in the non-dominant (left) and dominant hand (right). The results show much larger deviation in the group of children as compared to the two adult groups.

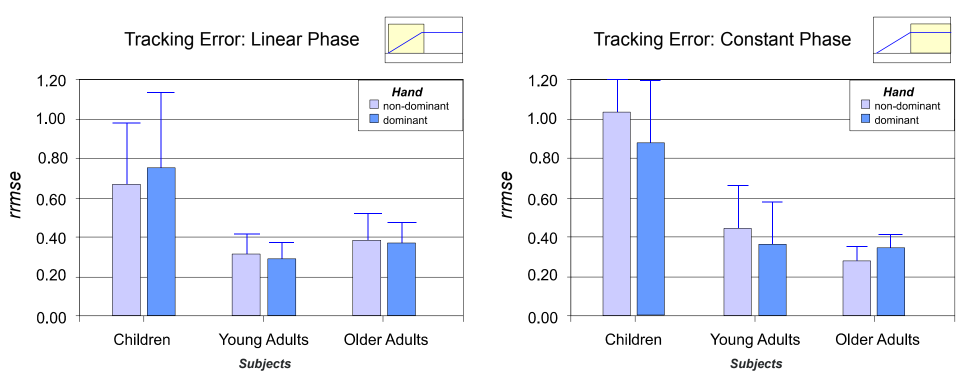

Figure 4.4: Average tracking error of the three groups during the linear increase and constant phase of the ramp signal.

The ramp tracking performance was further analyzed by calculating the tracking error. Figure 4.5 (left) shows the tracking errors of individual subjects as the scatter plot between the results obtained in the dominant and non-dominant hand. The results represent the performance of one trial with the ramp target. If the performance is equal in both hands, the result lies in the diagonal of the chart. The individual results of the two adult groups form two separated clusters while the group of children is more sparsely distributed. Figure 4.5 (right) presents the average tracking errors in the ramp task for all three groups. The average tracking error of children was 0.68 (SD 0.34) for the non-dominant hand and 0.64 (SD 0.19) for the dominant hand. The average tracking error in the group of younger adults was 0.31 (SD 0.01) for the non-dominant hand and 0.25 (SD 0.11) for the dominant hand. The average error in the older adults was 0.37 (SD 0.05) for the non-dominant hand and 0.44 (SD 0.09) for the dominant hand. The young adults performed the task with the greatest accuracy while the children demonstrated more than twice as large tracking errors. Slightly better performance was evident in the dominant hand but the difference was not statistically significant.

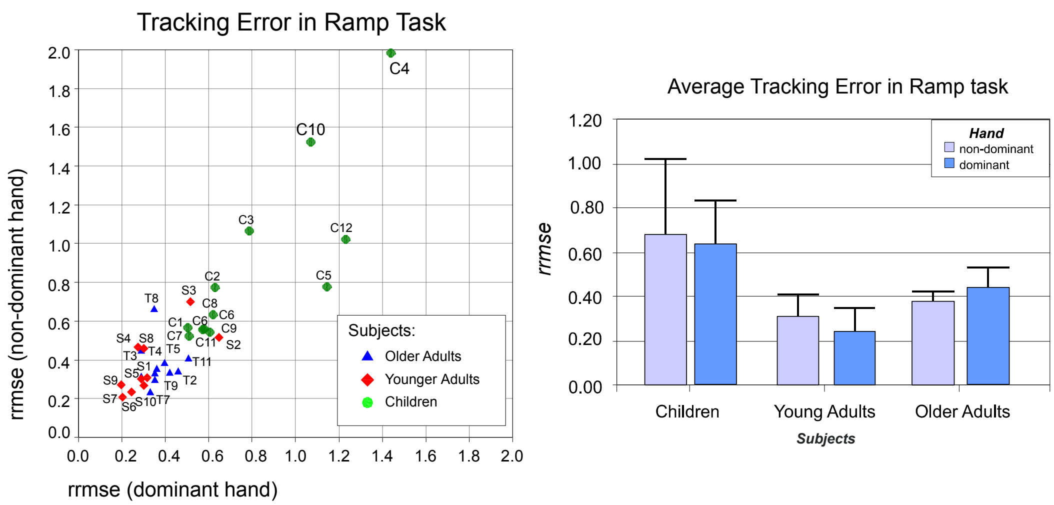

Figure 4.5: Scatter plot of the individual tracking results (left) and the average tracking error values (right) for the groups of children, young adults and older adults. No significant influence of hand dominancy was found when performing the ramp task.

Figure 4.6 shows the force output of tracking the sinus target as performed by three arbitrarily selected subjects, child C6, young adult subject S7 and older adult subject T10. The tracking output is presented in time domain and the corresponding force-velocity domain. The results show that the young adult performed the task with the lowest deviations from the target and produced a smooth response of the grip force. The child was unable to smoothly increase and decrease the grip force which resulted in more abrupt force response producing much larger tracking error. The corresponding trajectory in the force-velocity domain is presented on the right of Figure 4.6 showing a circular trajectory of the target and the trajectory of the measured grip force. The results of the young adult subject show a very smooth response, while the results of the child and the older adult show more irregular trajectory due to abrupt changes of the grip force. Both subjects used excessive force rates when increasing or decreasing the force.

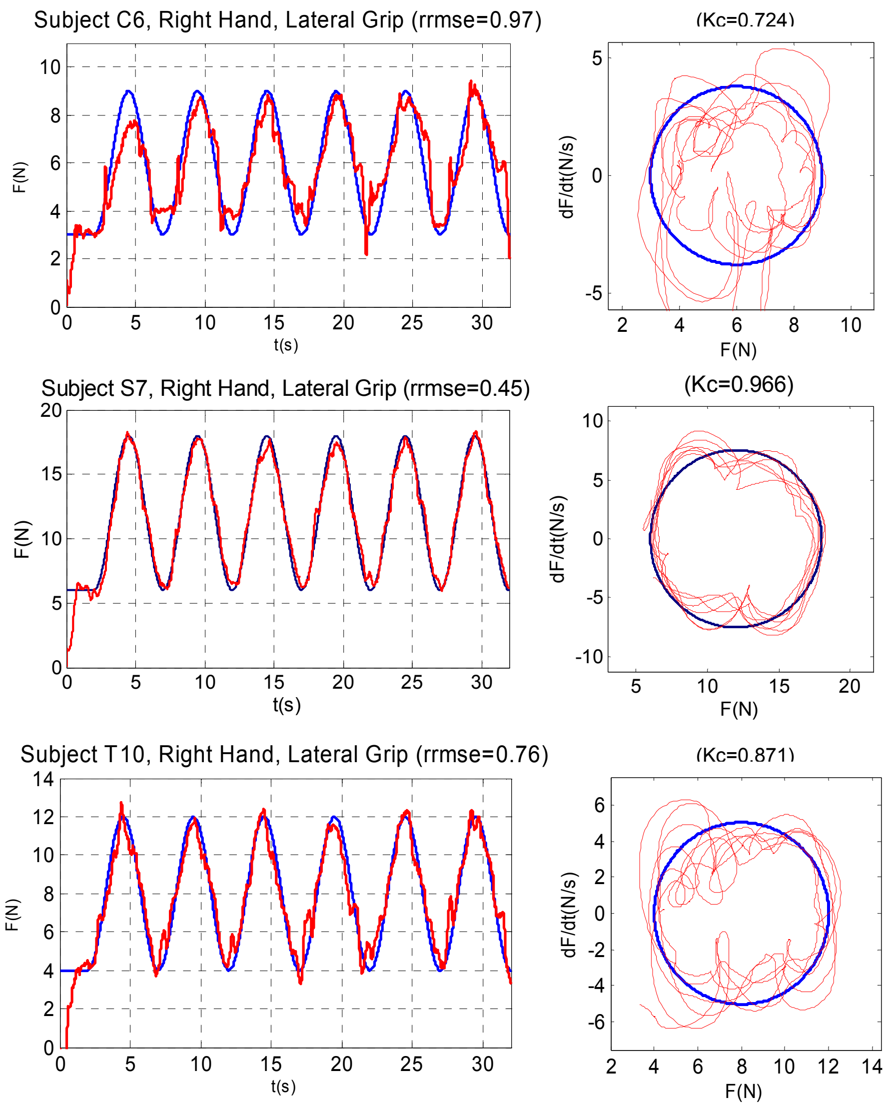

Figure 4.6: The results of the sinus task as assessed in child C6, young adult S7 and older adult T10 when using lateral grip. The measured response with respect to the target is shown on the left and the corresponding trajectory in the force-velocity space is shown on the right side.

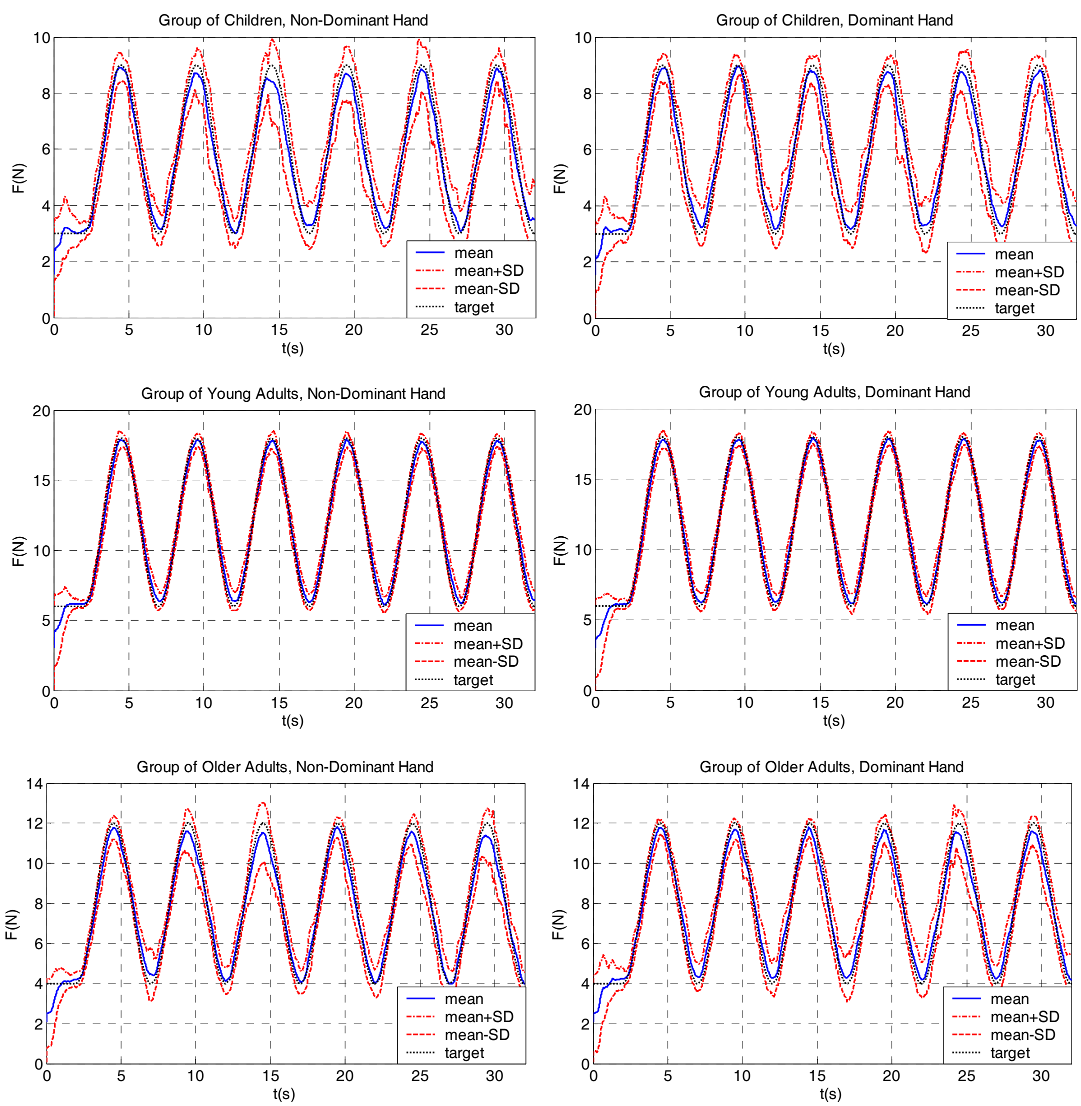

Figure 4.7: Average tracking outputs for the three age groups as obtained in the non-dominant (left) and dominant hand (right). The results show much larger deviation in the group of children and older adult subjects as compared to the group of young adults.

Figure 4.7 shows the average output signals with standard deviation as assessed in the sinus task in non-dominant and dominant hand. The results show significantly larger variability in the group of children and older adults as compared to the group of young adults. The average response in children shows overshooting of the sinus target. The young adults produced a smooth response with only small deviations.

The performance of the sinus task was further evaluated by calculating the tracking error as defined in equation (4.1). Figure 4.8 shows the tracking errors of individual subjects as the scatter plot between the results obtained in the dominant and non-dominant hand. The young adults performed the task with the greatest accuracy and the least variability. The results of older adults slightly overlap with the group of young adults, but the average tracking error values are much larger in the majority of the subjects. Three of the older subjects (T1, T3 and T8) performed the task with about 20% higher accuracy when using the dominant hand. The children produced more than twice as large errors in this task. The children C3, C9 and C11 performed the task with about 25% lower accuracy when using the non-dominant hand. The results of other subjects showed no significant influence of hand dominancy.

The results show significant differences in the tracking accuracy among the tested groups (one-way ANOVA, non-dominant hand: $F_{2,29}$=21.3, p<0.001, dominant hand: $F_{2,29}$=13.3, p<0.001). The largest tracking error was found in the group of children, 1.17 (SD 0.28) for the non-dominant hand and 1.12 (SD 0.37) for the dominant hand. The average tracking error of the young adults was 0.55 (SD 0.17) for the non-dominant hand and 0.52 (SD 0.17) for the dominant hand. The group of older adults had the average tracking error of 0.87 (SD 0.19) for the non-dominant hand and 0.81 (SD 0.22) for the dominant hand. The average results of all groups suggest slightly better grip force control in the dominant hand but the difference is not significant (one-way ANOVA, children: $F_{1,22}$=0.15, p=0.699, young adults: $F_{1,18}$=0.25, p=0.625, older adults: $F_{1,18}$=0.32, p=0.579).

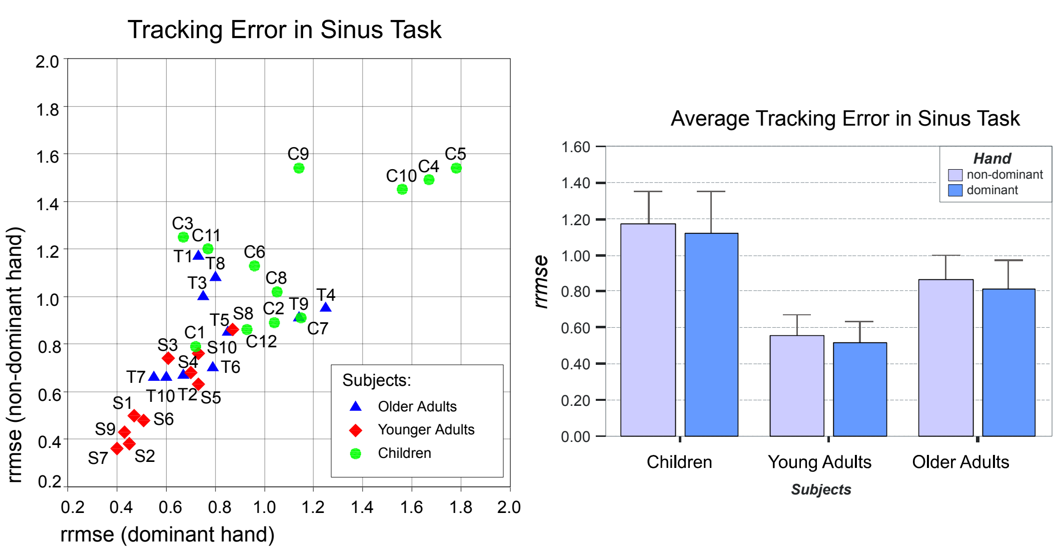

Figure 4.8: Scatter plot of the individual sinus tracking results (left) and the average tracking errors as obtained in three age groups of healthy subjects.

The subjects also tracked a periodic rectangular target but the results showed that most of the subjects adapted a strategy of predicting the course of the target signal instead of responding to the target. Subjects sometimes preceded the target therefore no consistent results were obtained for further analysis.

4.4.4 Discussion of Results

The tracking results show significant differences in average tracking performance among the three age groups. The ramp task was performed with much greater accuracy than the sinus task in all subjects. In both tasks the children produced more than twice as large errors as compared to the group of young adults. The larger tracking error in children suggests that in this age group the grip force control in dynamic tasks is not yet as developed as in adults. The analysis of the force-time curves of children shows similar findings in the sinus task as reported by Blank and colleagues [4], who assessed tracking of ramp target in 5-year old children. The 10-year old children in our investigation showed better performance in the ramp task as compared to reported results of the 5-year olds. When tracking the dynamic targets, the children tend to precede the target signal and then correct the output by reducing or increasing the force. This strategy results in more abrupt force outputs. The dynamic tasks, such as a sinus target tracking, require periodic muscle activation and more accurate adaptation of the grip force. The young adult subjects produced much smoother outputs suggesting that the grip force control further develops after the age of 10 years. The results show no significant influence of hand dominancy on the task performance in any of the groups. Analyzing the tracking results of individual subjects showed much larger variability among the children as compared to the younger adults. The older adults produced non-smooth trajectories with large deviations from the sinus target. The results suggest that the grip force control as well as the overall sensory motor functions are reduced with age. No significant influence of hand dominancy on the task performance was found although the performance was slightly better for the dominant hand. Study by Kabbash and colleagues [52] suggests that in visual-motor tasks with the emphasis on accuracy of movement the dominant hand is superior when large contraction of muscles is required while no difference is evident in smaller movements.

4.5 Grip Force Control in Patients with Neuromuscular Diseases

Progressive neuromuscular diseases include diseases of anterior horn cell, motor neuron, peripheral nerve and neuromuscular junction [113]. Majority of neuromuscular diseases are hereditary and incurable. In some cases physical rehabilitation and drug treatment can slow down the progress of the disease. The main symptoms of neuromuscular diseases include progressive muscular weakness and increasing fatigue which result in decreased mobility and functionality of the limbs. Other functions such as swallowing, chewing, speaking or breathing can also be affected. Many patients develop contractures which further impair functionality of the upper limbs.

Several types of neuromuscular diseases exist:

- *Limb-girdle muscular dystrophy* is mainly affecting shoulder or pelvic girdle muscles with variable rates of progression. The disease can affect males and females, usually in the late first or second decade of life. Muscular weakness may progress from the lower limbs to the upper limbs or vice versa, affecting the proximal muscles more than distal. The weakness is predominantly symmetrical.

- *Facioscapulohumeral muscular dystrophy* is characterized by an asymmetrical weakness of the shoulder girdle muscle, spreading to finger and wrist extensors.

- *Spinal muscular atrophies* are caused by degeneration of anterior horn cell. The distribution of weakness is symmetrical and affects proximal muscles of the lower limbs more than the distal muscles and muscles of the upper limb.

- *Duchenne Muscular Dystrophy* is caused by gene mutation terminating the production of muscle protein dystrophin. The disease is affecting only males. The muscular weakness is first evident in the muscles of the pelvic girdle and later spreads to the rest of the muscles. A milder form of Duchenne dystrophy is *Becker Muscular Dystrophy*. Duchenne/Becker dystrophies can be asymmetrical initially but later affect both limbs symmetrically [27, 113].

Reliable evaluation of neuromuscular condition is important to determine results of therapeutic interventions and to evaluate the progress of the disease. The evaluation tests should be disease-specific [113]. Clinical evaluation methods include manual muscle test (MMT), clinical neurological examinations and various rating scales [121]. The methods often lack objectivity and sensitivity needed to detect small changes in muscular strength due to the progress of the disease. The aim of our study was to determine to what extent the grip force control is affected by different neuromuscular diseases [62]. The patients tracked different targets aimed to assess the grip strength, muscle fatigue and grip force coordination. Different grip types were considered for evaluation. In patients with neuromuscular diseases not all the muscles of the arm and hand are affected to the same extent. In some conditions asymmetry of the muscular weakness is present, as well as uneven degree of disability between the distal and proximal muscles. We expected that in some patients there would be a considerable difference in performance among tested grips when using left or right hand.

4.5.1 Subjects

The grip force control was analyzed in 20 patients with neuromuscular diseases (mean age 35.7 (SD 11.4) years), 13 of them were female and 7 were male (Table 4.4). The control group consisted of 9 healthy male volunteers (mean age 28.4 (SD 3.4) years) (Table 4.2). All participants reported right-hand dominance. The patients were diagnosed with the following types of neuromuscular diseases: LGMD - Limb-Girdle Muscular Dystrophy, FSHMD – Facioscapulohumeral Muscular Dystrophy, SMA3 - Spinal Muscular Atrophy type 3, SMA2 - Spinal Muscular Atrophy type 2, and BMD - Becker Muscular Dystrophy (Table 4.4).

Table 4.4: Data of the patients with neuromuscular diseases

Patient	*Gender*	*Age*	*Diagnosis*	*Patient*	*Gender*	*Age*	*Diagnosis*
P0	M	48	LGMD	P10	M	26	BMD
P1	F	28	FSHMD	P11	M	46	SMA3
P2	M	35	SMA3	P12	F	27	SMA2
P3	F	28	SMA2	P13	M	24	SMA2
P4	M	23	BMD	P14	M	45	SMA3
P5	F	28	SMA3	P15	M	49	FSHMD
P6	M	32	BMD	P16	F	51	FSHMD
P7	F	50	SMA3	P17	M	59	LGMD
P8	M	23	LGMD	P18	F	32	LGMD
P9	M	36	LGMD	P19	M	24	BMD

4.5.2 Methods

The tracking performance was assessed in five different grips: cylindrical, lateral, palmar grip, pinch and spherical grip, evaluating the dominant and non-dominant hand. Two different tracking tasks were selected for the evaluation of the grip force control. The first task consisted of tracking a ramp target which increased in 15 s from the initial value of 0 N to the final value of 30 N for nippers pinch, 60 N for lateral and 70 N for spherical and cylindrical grips. The peak values for each grip were selected based on our preliminary investigation involving patients with neuromuscular diseases and correspond to about 30% of the maximal voluntary grip force in healthy subjects [75]. The patient was instructed to track the target as long as possible and, if unable to exert the required force, to keep the grip active until the end of the trial. Each trial lasted 32 seconds. The second task consisted of tracking a sinusoidal target with the frequency of 0.2 Hz. The amplitude of the signal was set individually at about 30% of the patient's maximal grip force as assessed in the ramp trial. During the assessment the patient was asked to maintain consistent grip and was not allowed to use 'trick' movements (e.g. influencing the grip force by changing arm orientation or leaning onto the device). A therapist monitored the patient's hand posture and the test was repeated if the requested procedure was not followed. If a patient was unable to perform the grip within the required hand and arm position due to contractures, the position and orientation of the grip-measuring device were adjusted to find the most adequate posture. Each patient first performed one test trial of the tasks and then two trials of each tracking task were recorded for each grip type. The more accurate performance was considered in further analysis. The same testing procedure was followed for the control group of healthy subjects.

4.5.3 Results

The first task consisted of tracking a ramp target. The results of the test reflect the patient's grip force control when gradually increasing the grip force. The maximal force level reached was used to quantify the strength of individual patient while applying different grips on the end-objects of the grip-measuring device. Figure 4.9 shows the results of the ramp as performed by two patients (P15 and P12) using cylindrical grip. The patient P15 was able to track the target while increasing to about 40 N but was unable to retain the force rate until the end of the trial despite sufficient grip strength to briefly reach the peak force level of 70 N. The effect of muscular weakness is especially evident in the second patient (P12) who was able to reach only about 30% of the target force level. The patient tried to retain the maximal output force as instructed but his force gradually decreased due to muscle fatigue.

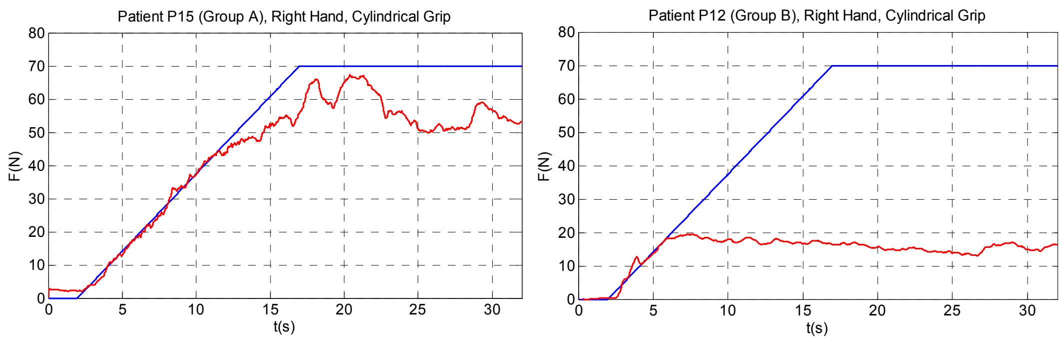

Figure 4.9: The results of the ramp tracking as assessed in two patients with neuromuscular diseases (P15 and P12) show evident muscular weakness and fatigue when performing that task with the cylindrical grip.

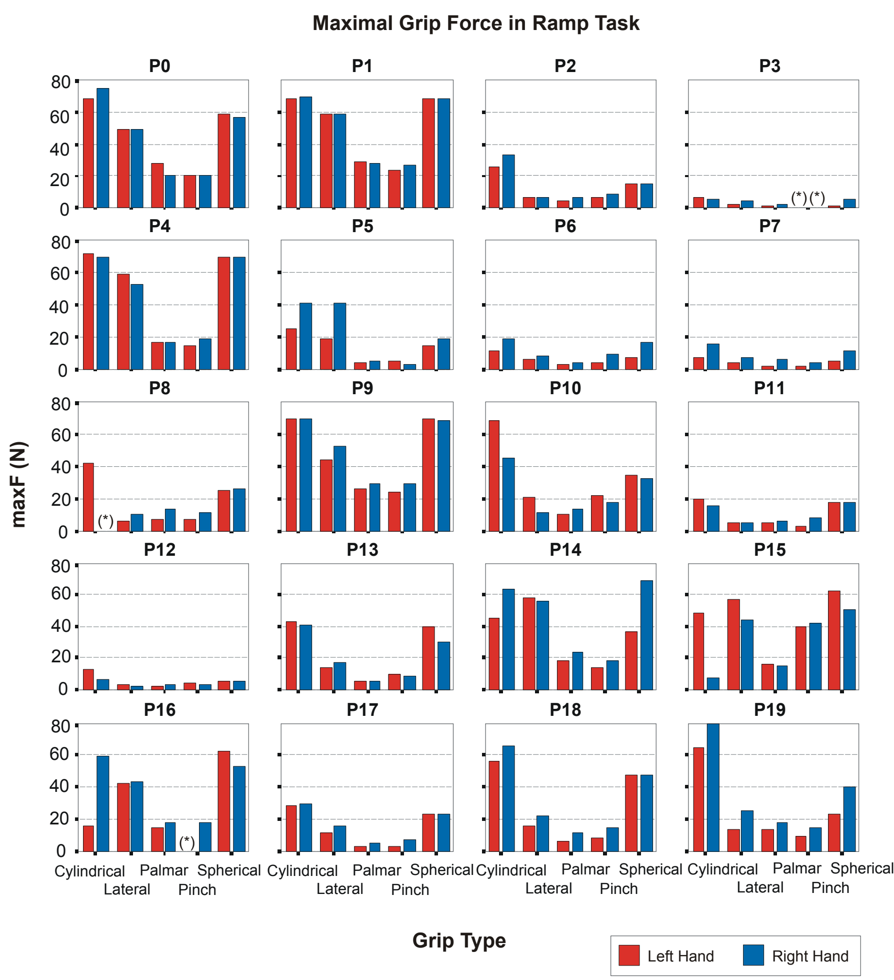

Figure 4.10: The maximal grip forces of 20 patients with neuromuscular diseases as assessed in the ramp task are compared within different grips. The normal peak values of the ramp target were 30 N for nippers pinch and palmar grip, 60 N for lateral grip and 70 N for spherical and cylindrical grips. (* Patient was not able to perform the indicated grip)

Figure 4.10 shows the results of the maximal grip forces as assessed in 20 patients who performed the ramp tracking task with five different grips (cylindrical, lateral, palmar, pinch and spherical grip). The maximal grip force was determined as the average force sustained for the duration of 5 seconds at the point where the target first reached its maximal value. The obtained value was compared to the target levels of the healthy subjects. The patients P2, P3, P6, P7, P8, P11, and P12 were not able to exert higher-level grip forces in any of the grips tested. Majority of these patients were diagnosed with SMA (Type 2 and 3) which symmetrically affects both hands. Asymmetrical weakness was most evident in patients P10, P15, P16, and P19 diagnosed with FSHMD or BMD.

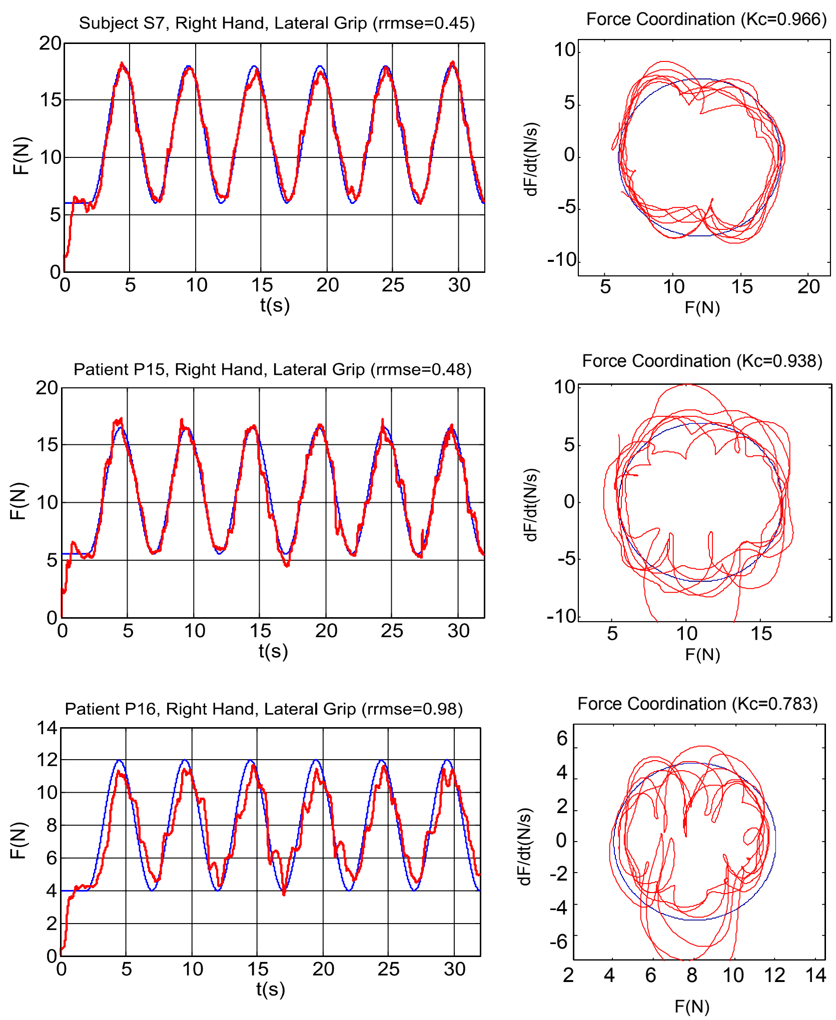

Figure 4.11: The results of the sinus task as assessed in healthy subject S7 and two patients with neuromuscular diseases (P15 and P16) when using lateral grip. The measured response with respect to the target is shown on the left and the corresponding trajectory in the force-velocity domain is shown on the right side.

The second task consisted of tracking a sinusoidal target to assess patient's grip force control during periodic activation of muscles. The performance of the task was assessed by calculating the relative tracking error (*rrmse*) and coefficient of coordination (K_c). Figure 4.11 shows the results of the tracking in lateral grip as obtained in one healthy subject (S7) and two patients (P15 and P16). The healthy subject accurately followed the target (*rrmse*=0.45) and produced a smooth response with small deviations. Comparing the results between the two patients shows that the patient P16 had more difficulty adapting the grip force and produced much higher tracking error (*rrmse*=0.98) than the patient P15 (*rrmse*=0.48). The grip force response of the patient P16 reveals more abrupt muscle activation patterns that unable her to gradually increase or decrease the grip force. Figure 4.11 (right) shows the circular trajectory of the target and trajectory of the measured output in force-velocity domain. The two patients produced less smooth response as compared to the healthy subject. The results of the patient P16 show more irregular trajectory due to excessive force rate used while tracking the sinusoidal target.

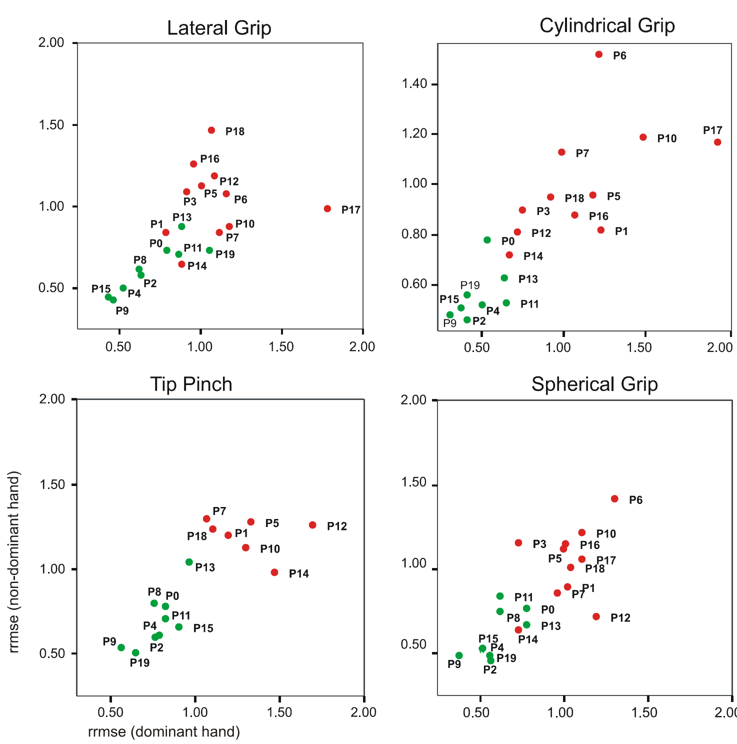

Figure 4.12: Scatter plots of individual tracking results for four different grips as assessed in the dominant and non-dominant hand. The analysis with k-means clustering algorithm showed grouping of patients in two functional groups.

The results of the tracking error varied significantly among the patients, therefore we tried to identify functional groups with similar tracking performance. Figure 4.12 shows scatter plots of the tracking error for four of the grips. The analysis of the results showed that some of the patients (e.g. P2, P4, P9, P15) produced tracking errors in the range of the healthy subjects (see Figure 4.8) while others (e.g. P6, P12, P17, P18) produced more than twice as large tracking errors. We applied k-means clustering algorithm [34] to group the patients by their tracking performance. Two clusters were identified based on how the tracking results between the dominant and non-dominant hand in different grips were scattered in the plane. The first cluster was denoted as "*group A*", containing 11 patients with larger tracking errors and the second cluster was denoted as "*group B*", containing 9 patients with lower tracking errors. The group A included patients: P1, P3, P5, P6, P7, P10, P12, P14, P16, P17, and P18. The group B included the remaining patients: P0, P2, P4, P8, P9, P11, P13, P15, and P19. The two functional groups obtained by the clustering algorithm divided the patients based on their grip force control.

Table 4.5: Average tracking error and coordination coefficient in the three groups.

	TRACKING ERROR (*rrmse*)		COORDINATION COEFFICIENT (K_C)	
	non-dominant hand	*dominant hand*	*non-dominant hand*	*dominant hand*
HEALTHY SUBJECTS	0.53 (0.16)	0.52 (0.17)	0.915 (0.049)	0.915 (0.062)
GROUP A	1.10 (0.25)	1.15 (0.29)	0.691 (0.120)	0.652 (0.169)
GROUP B	0.64 (0.14)	0.66 (0.16)	0.879 (0.042)	0.869 (0.066)

In Figure 4.13 the average tracking errors and the coefficients of coordination as assessed in the two groups of patients are compared to the results of the healthy subjects. The patients in group A produced on average about twice as large tracking errors (Table 4.5). The results of both groups indicate that most patients produced larger tracking errors in nippers pinch or tip pinch as compared to the other grips (Figure 4.13). Both patient groups show significant effect of the grip type on the tracking accuracy in the dominant hand but no significant effect was found in the non-dominant hand (one-way ANOVA, non-dominant hand: $F_{4,48}$=2.221, p=0.81, dominant hand: $F_{4,48}$=4.867, p=0.002; group B: non-dominant hand: $F_{4,40}$=1.291, p=0.290, dominant hand: $F_{4,39}$=3.193, p=0.023). The healthy subjects performed the task with similar accuracy regardless of hand dominance or grip type (non-dominant hand: $F_{4,40}$=0.812, p=0.525, dominant hand: $F_{4,40}$=1.175, p=0.337). The tracking error results suggest that the patients from group B have more enhanced muscle control because they could perform the task with similar accuracy in all tested grips as the healthy subjects. Comparing the average tracking results of the two patient groups to the healthy subjects showed significant difference in performance of the task (group A: $F_{1,194}$=334.4, p<0.0001, group B: $F_{1,177}$=28.72, p<0.0001).

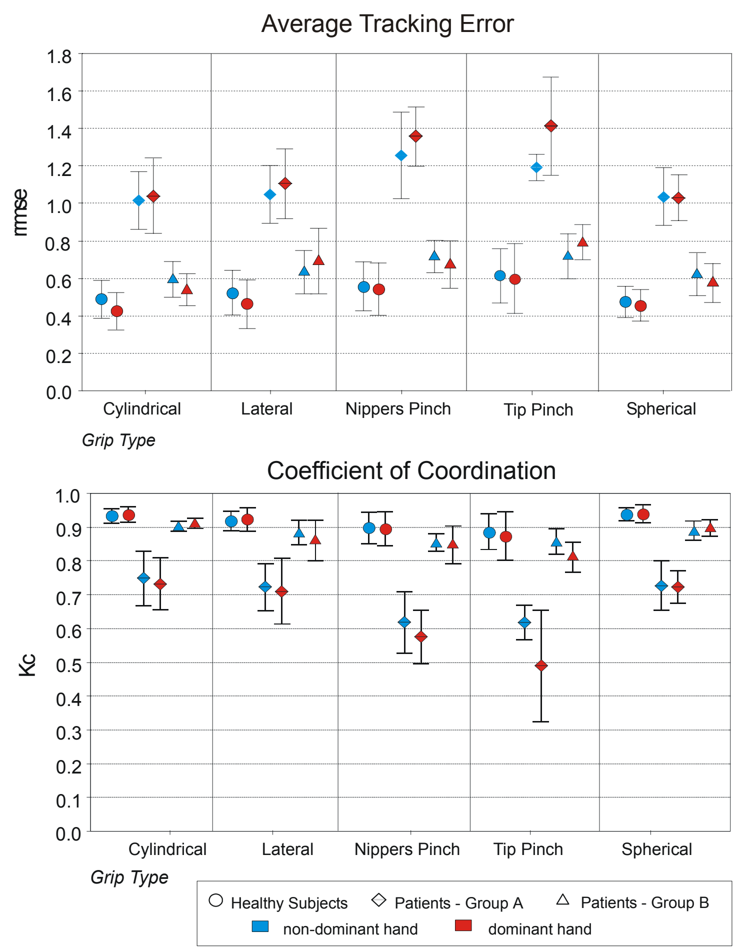

Figure 4.13: The average tracking error (above) and the average coefficient of coordination (below) in different grips as assessed in the healthy subjects and the two groups of patients (A and B).

The analysis of the average correlation coefficient showed significant differences between the two patient groups and the healthy subjects (group A: $F_{2,195}$=22.24, p<0.0001, group B: $F_{2,177}$=24.98, p<0.0001). The results of both patient groups suggest that the dynamics of the force largely depends on the muscle groups used in particular grip. No significant effect of the grip type was found in healthy subjects (non-dominant hand: $F_{4,40}$=2.001, p=0.113, dominant hand: $F_{4,40}$=2.130, p=0.095), which suggests that the muscle groups of healthy subjects more accurately adjust the dynamics of the exerted force while performing the tracking task (Table 4.5). Further analysis of the results of this study can be found in [62].

4.5.4 Discussion of Results

The results of the ramp test showed that the test could be used to identify asymmetry in muscular weakness and quantify muscle fatigue. The information is important when evaluating the progress of a neuromuscular disease [113, 121]. The results of the ramp task showed asymmetrical performance in most of our patients diagnosed with FSHMD and BMD. Most of the patients diagnosed with different types of SMA, which symmetrically affects the muscles, showed equal performance of the test with both hands.

The results of the sinus tracking showed that the method can evaluate the grip force control in different types of grips, providing information on hand dexterity, muscle activation patterns and tremor. Comparing the results of tracking with a group of healthy subjects suggests that in some patients the disease did not affect their grip force control despite the evident muscular weakness. Some of the patients used excessive force rates when tracking the sinusoidal target. Most patients produced larger tracking errors in nippers pinch and tip pinch as compared to other grips. The two grips are characterized as precision grips and require precise motor control of the muscles. The healthy subjects and the group of patients with better grip force control demonstrated less significant differences among the grips tested. Both groups of patients had much larger variability in dominant hand when performing the task with different grips as compared to the healthy subjects.

The presented system can measure the grip force with much higher accuracy as compared to the conventional instruments used in clinical practice which often lack the sensitivity to detect small changes. The results of tracking a periodical signal such as a sinus can be used to analyze the activation patterns of muscles used while increasing or decreasing the grip force. The assessment could be further improved by simultaneous measurement of electromyographic (EMG) signals to analyze the activation patterns of different muscle groups. While the ramp task correlated with different diagnoses, no significant links between patient's grip performance of the sinus tasks and diagnosis were found. Due to the nature of neuromuscular diseases, where patients with the same form of disease can be affected to a different degree, a larger scale study is needed to include patients with similar functional abilities in groups with specific diagnoses.

4.6 Grip Force Control after Botulinum Toxin Treatment: Case Study

Botulinum toxin (BTX) is clinically used for treatment of spasticity. BTX is produced by anaerobic bacterium *Clostridium botulinum*. The toxin has a paralytic effect on the muscle by blocking neuromuscular transmission. When injected into a muscle, chemical denervation of nerve endings is initiated resulting in local paralysis. The toxin affects the nerve area only for a limited period of time. The nerve sprouting and muscle re-innervation return the functional ability of the injected muscle within 2 to 4 months. Several immunologically different types of BTX exist but only type A (BTX-A) is in clinical use at the time. BTX-A treatment is used for treatment of different conditions such as focal dystonia (i.e. neurological movement disorder) and spasticity in stroke, traumatic brain injury, cerebral palsy and multiple sclerosis [21]. The treatment is often combined with physiotherapy, use of orthoses, functional electrical stimulation and oral medications to possibly achieve long-term effects of the treatment. Side effects include local weakness of the muscle, difficulty of swallowing, and in rare cases flu-like symptoms [21]. In the treatment of upper-limb spasticity, the reduction of grip strength is expected due to reduced muscle tone of the injected muscle [10]. The major limitations of BTX use are in the cost of the therapy and the need for repeated injections after the initial treatment. A patient can also develop antibodies and further BTX treatment becomes ineffective.

To evaluate the effectiveness of BTX treatment in combination with other therapeutic methods, objective and quantitative assessment of muscle strength and motor control during the recovery period is needed. The sensitivity of functional scales of the upper extremity tests is often too small to detect changes after the treatment [10]. Conventional dynamometer testing lacks the accuracy to evaluate the progress of muscle recovery. The aim of our investigation was to evaluate the influence of injected BTX on the grip force control and muscular strength using the tracking method.

4.6.1 Subject

Three subjects who received BTX injection were initially selected for this study but only one of the subjects was available for all the follow-up measurements. In this chapter we present the results of a 38 year-old female patient, who 8 years ago suffered a traumatic brain injury resulting in the right-side hemiparesis. Precision grip on her right side was preserved but the patient had difficulties grasping objects due to developed spasticity and loss of muscle control. The patient was treated with BTX injection into the wrist and finger flexor muscles.

4.6.2 Methods

We evaluated the patient's grip force control of the lateral grip one day before receiving the treatment and 6 and 13 weeks afterwards. The patient showed reduced ability to control the flexors of the thumb and fingers therefore lateral grip was selected for evaluation. The patient performed three different tasks: ramp, sinus and rectangular task. The ramp task was aimed to assess the muscle fatigue during the recovery period which is a common side effect of BTX therapy. The accuracy of the grip force control was evaluated by the average tracking error of three trials in the sinus task. The rectangular task was aimed to show the effect of the treatment on the opening and closing of the grip between two force levels. The assessment procedure was supervised by a physical therapist.

The patient's hand function was also clinically evaluated before the application of BTX, 72 hours afterwards and then 6, 8, and 13 weeks after the application. The spasticity was evaluated by modified Ashworth scale, the motor function with Motor Assessment Scale (MAS) [91] and Canadian Occupational Performance Measure (COPM).

4.6.3 Results

The results in Figure 4.14 show patient's performance of the ramp task before and after BTX treatment. The results in the unaffected hand show similar performance in both sessions. The patient was able to accurately track the ramp target and retain the required grip force level. The results of the affected hand before the treatment show that the patient tracked the target with larger deviations as compared to the unaffected hand. 13 weeks after the treatment, patient's grip strength was reduced and fatigued faster. The patient was unable to retain the required grip force level after reaching the peak value of the ramp target. The results in the ramp task clearly show the effect of the BTX on the reduction of muscle tone.

Figure 4.15 shows the results of tracking the sinusoidal target before and after the therapy. The results obtained in the unaffected hand show only small changes in performance after the treatment. The muscle control in the affected hand improved considerably after 13 weeks. The patient produced significantly smaller deviations from the target. Before the treatment, the patient had difficulty opening the grip and was unable to reach the minimum peaks of the sinus signal (Figure 4.15, top-right). After the therapy, the release of the grip improved and the patient was able to track the target more accurately (Figure 4.15, bottom-right). The resulting grip force output was much smoother. The patient was able to increase and decrease the force within the required range.

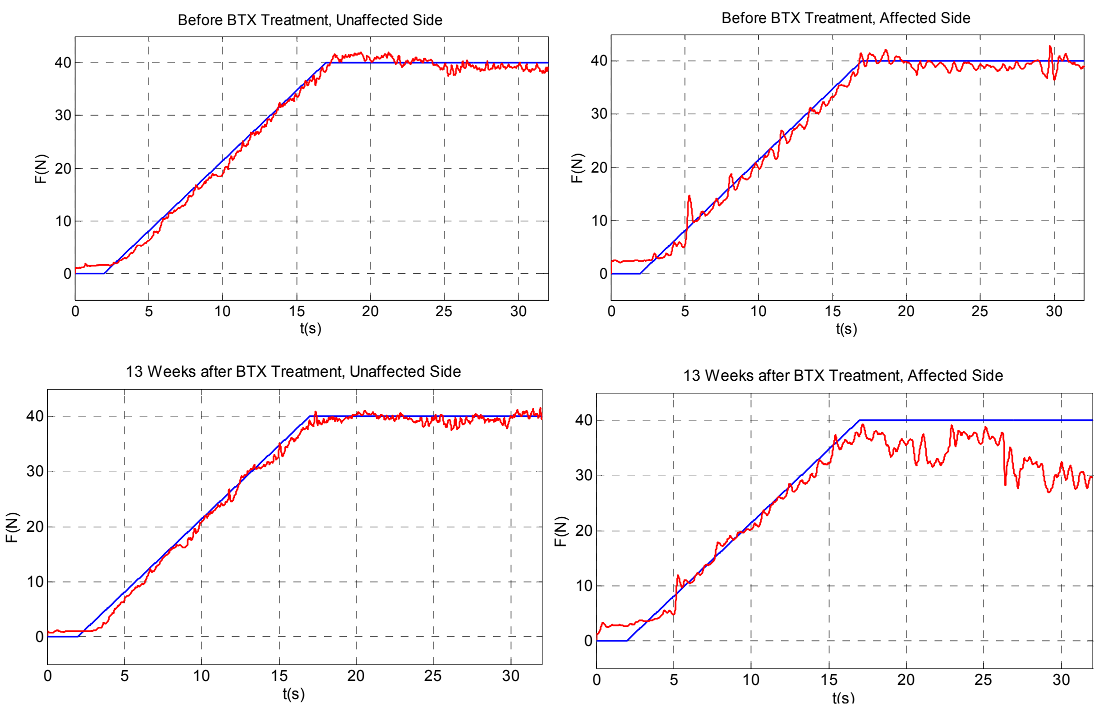

Figure 4.14: Tracking results of the ramp task before (top) and 13 weeks after (bottom) BTX treatment show visible increase of fatigue and muscular weakness in the affected hand (right) as compared to the unaffected hand (left).

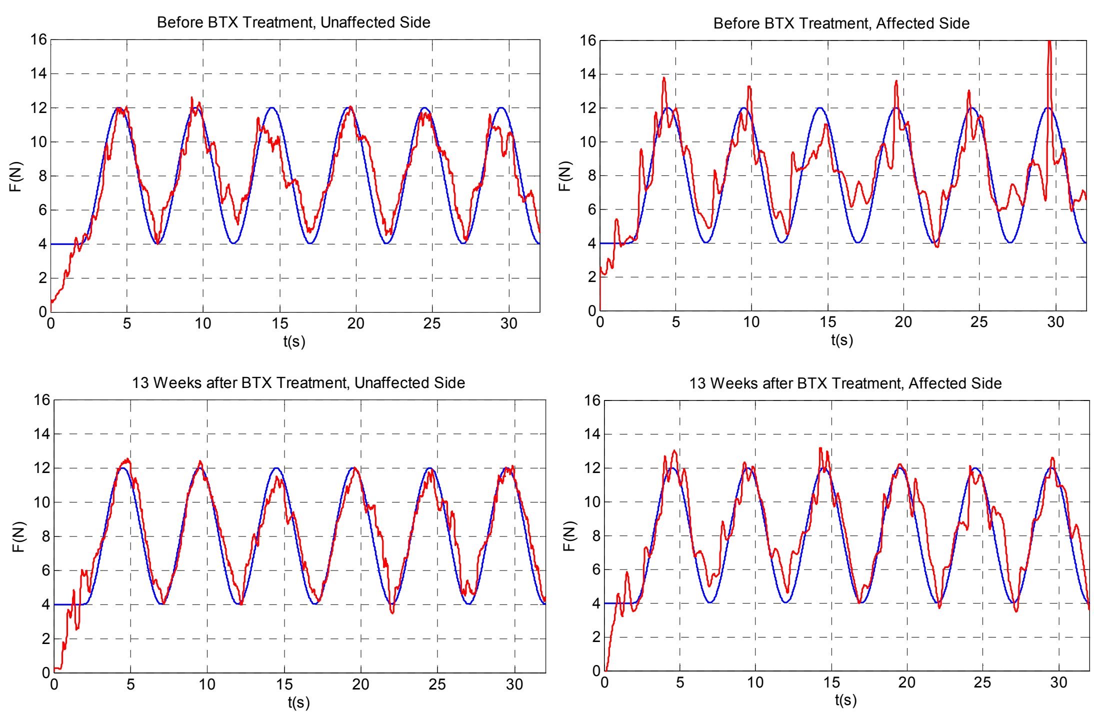

Figure 4.15: Tracking results of the sinus target tracking before and 13 weeks after the BTX treatment show visible improvement in the grip force control.

Figure 4.16 shows the average tracking error as obtained in the sinus task before and after the treatment. The results show the mean tracking error of three trials with standard deviation as obtained in each session. The patient produced considerably larger tracking errors with the affected hand as compared to the unaffected hand before receiving the treatment (Paired-samples t-test, $p<0.05$). After 13 weeks the patient improved her performance with the affected hand for about 30%, much smaller improvements in force control were visible when the task was performed with the unaffected side. The results of the rectangular task can be found in [63].

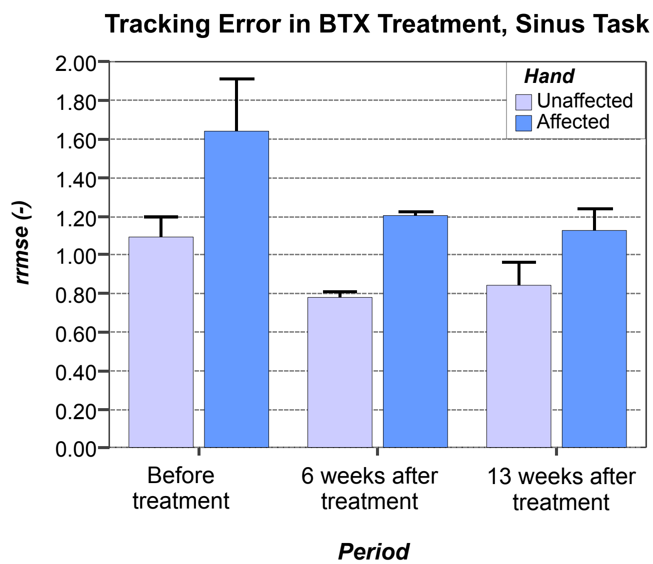

Figure 4.16: Average tracking error as obtained in the sinus task before and after the BTX treatment. The results show considerable improvement in the grip force control of the affected hand after the treatment.

4.6.4 Discussion of Results

The most common side effects of the BTX treatment are reduced muscle capacity resulting in weakness and increased fatigue of the injected muscle. Our previous investigation of grip force control assessment in patients with neuromuscular diseases [62] showed that the ramp tracking task is a valuable indicator for the evaluation of muscular weakness and muscle fatigue. The results of this investigation showed that before the treatment the patient was able to track ramp target within the required force range. After BTX was injected into the flexor muscles, the muscular weakness was clearly visible when performing the ramp task with the affected hand.

When tracking the sinusoidal target before the treatment, the patient had difficulty controlling the grip force of the affected hand. Due to spasticity of the flexor muscles, the patient was unable to completely release the grip and produced abrupt force response resulting in much larger tracking error. When increasing the force in the rectangular target tracking [63], the patient used excessive force and was unable to retain the required force level. After the treatment with BTX and the physical therapy received during this period, the grip force control of the affected hand significantly improved and the patient produced much smoother grip force response.

The patient's hand function was clinically assessed by means of Canadian Occupational Performance Measure (COPM) which is mainly focused on the evaluation of different functional movement tasks of the entire arm thus providing less information on hand function and the control of force. The tasks included in COPM evaluation, which require accurate force control of the hand and fingers, are writing and feeding tasks. The patient showed improvement in writing (before: 4, after: 7) and feeding (before: 2, after: 8) with the affected hand 12 weeks after the therapy. The results of the tracking and the clinical measure suggest improvements in the motor control of the affected muscles. Further study is needed to investigate the sensitivity of the tracking method to validate the effects of BTX treatment.

5 Training of Grip Force Control

Many studies have shown beneficial effects of repetitive sensory-motor training in persons after central nervous system injury [40, 59, 93, 109]. The repetitive training can initiate relearning process inside the central nervous system and contribute to the enhancement of motor skills. Computer tasks with visual feedback provided to a patient during therapy represent an important area of research in future rehabilitation. The tracking method as a rehabilitation therapy was presented by Kriz and colleagues [59] who showed the positive influence of such therapy on the restoration of the grip force control in patients after traumatic brain injury. In our study we focused on patients after stroke. We designed a set of tasks aimed to improve the grip force control and enhance the ability to balance and release the grip. The proposed tracking system was applied as a training method in 10 post-stroke patients to possibly improve their grip force control. The patients trained daily over a period of four weeks in combination with the conventional physical and occupational therapy.

5.1 Grip Force Measuring System

Based on the experience with the first prototype of the force measuring device used for the assessment of grip force control [61, 62], a new grip-measuring system with one dimensional force sensor was developed. The measuring system was redesigned to produce more compact device, which can be connected to a laptop or desktop computer through standard parallel port and to reduce the costs of the sensor unit. The new system consists of two force-measuring units of different shapes (cylinder and thin plate) which are connected to a personal computer through an interface box (Figure 5.1). Each device consists of a single point load cell (PW6KRC3 or PW2F-2, HBM GmbH, Darmstadt, Germany), which is mounted on a metal construction. The shape and the size of the measuring units are similar to the objects used in daily activities (e.g. cup and key). The cylindrical device allows the assessment of forces up to 300 N with the accuracy of 0.02% over the entire measuring range. The second device is made up of two metal parts which shape into a thin plate at the front end, resembling a flat-shaped object (e.g. a key). The load cell used can measure forces up to 360 N with the accuracy of 0.1%. Both units were calibrated by placing different weights at the point of contact of the measuring object to obtain the voltage-force characteristics. The electronic circuit of the interface box consists of an amplifier with supply voltage stabilizer and an integrated 12-bit A/D converter (MAX197, Maxim Integrated Products, Inc., Sunnyvale, CA, USA) capable of sending data to the parallel port of a personal computer [107]. The maximal supported sampling frequency of the force measurement is 1 kHz.

Figure 5.1: A compact assessment system with two force measuring units in the shape of a cup and thin plate was designed to measure dynamic grip force in cylindrical and lateral grip.

5.2 Training in Patients after Stroke

5.2.1 Subjects

Ten patients after stroke, 4 females and 6 males, ages 19 to 79 participated in this investigation (Table 5.1). Four of the patients had a left-side hemiparesis and the other six had a right-side hemiparesis. The time between the onset of the condition and the training was between 1 to 6 months for most patients. The patients were attending regular occupational therapy program, which was mainly focused on performing daily living activities. The patients were considered to be rehabilitated to a large extent. The patient's motor functions were evaluated by the modified Ross functional test [37] used by the therapists of the occupation department of Institute for Rehabilitation Republic of Slovenia. The test consists of the assessment of the upper extremity during different functional tasks: lifting of the arm above the head, moving the hand to the mouth, putting the hand behind the back, flexion and extension of the arm, supination and pronation of the hand, grasping an object, grasping and releasing an object, hand opening, precision grasping and releasing of a small object. The performance of each task is scored by a score from 0 to 5. The maximal possible score is 50. The patients were only assessed at the time of entering and leaving the occupational therapy which does not necessarily correspond to the period of training with the tracking methods. The method is not standardized and therefore the results are only given for illustrative purpose.

Table 5.1: Data of the patients after stroke

Patient	*Age*	*Gender*	*Hemiparesis*	*Time since onset*	*Grasp trained*	*Score at entering*	*Score at leaving*
P1	28	M	right	19 months	lateral	46	46
P2	20	M	left	6 months	cylindrical	31	35
P3	19	F	right	1 month	cylindrical	48	50
P4	44	M	right	1 month	lateral	10	12
P5	43	F	left	4.5 months	lateral	39	50
P6	49	M	right	3 months	lateral	12	21
P7	51	F	right	6 months	lateral	42	47
P8	36	F	right	6 years	cylindrical	22	22
P9	72	M	left	1 month	cylindrical	26	39
P10	79	M	left	4 months	cylindrical	25	30

5.2.2 Methods

Two different visual representations of the tracking tasks were used for the training. For the assessment of the maximal grip strength a blue bar with the height proportional to the applied grip force was presented on the screen. When the force was applied to the measuring object, the height of the bar increased in real time (Figure 5.2, above). Simultaneously a green mark indicating the value of the grip force as obtained in the previous trial was shown. If the patient applied a higher force, the blue bar pushed the green mark to a new position. If the patient was unable to reach the target force of the previous trial, the target of the next trial was set to the force level the patient could achieve. The information on the previous performance was indicated to encourage patients to try to improve their grip strength from the previous session.

The remaining tasks required patients to track a changing target by applying appropriate force to the force-measuring unit. The tracking task was presented in the same way as described in the previous chapters. Three different target signals were used for the training of the grip force control: tracking of randomized ramp and rectangular signals and tracking of a sinus signal with the increasing frequency. The properties of the signals were selected by the occupational therapists. To reduce the effect of learning and drop of attention span, randomized signals were used instead of periodic signals. The randomized ramp target was applied to train patient's muscular control when gradually increasing or decreasing the grip force. The randomized rectangular target was mainly focused on closing and opening of the hand between different discrete force levels to enhance patient's grasp stability and hand opening. The sinus target with the increasing frequency was aimed to improve accuracy of the grip force control. The signal amplitudes included levels reaching up to 30% of the patient’s maximal grip strength and the values of 0 N where the patient had to completely release the grip.

A graphic user interface was programmed in Matlab to allow simple selection of different tracking tasks and automated data storage for each patient in the database. The patients trained with the affected side for about 15 minutes daily, 4 to 5 times a week for four weeks. The progress of the rehabilitation was evaluated by the tracking error. The unaffected side was tested once every week to obtain reference results of each individual. During each training session the maximal grip force was first assessed using the bar task. The obtained value was used to set the amplitude of the three tracking tasks which was automatically set at 30% of the patient’s maximal grip force. The patient then performed the three tracking tasks, each lasting 60 seconds. After the training, patient's maximal grip force was assessed again. Patients either used the lateral grip or cylindrical grip, depending on the functional state of their affected hand. The selection of the grip was made during the first training session when each patient tried to perform the tasks on both force-measuring units. The training sessions were supervised by physical therapists.

The performance of tracking was quantified by calculating the relative tracking error as defined in equation (4.1). Paired-samples t-test was used to compare the differences in the performance at the beginning and the end of training for each patient. We considered p-values of 0.05 or less as statistically significant. The statistical analysis was performed with SPSS software (Lead Technologies, Inc., Chicago, IL, USA). Logarithmic regression was used to analyze the performance trends of the daily tracking results of each patient.

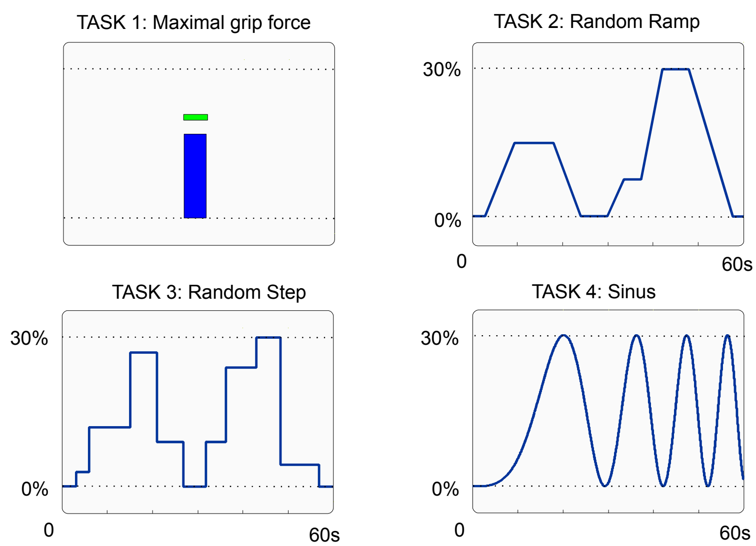

Figure 5.2: The stroke patients were trained with four different tasks: the assessment of maximal grip force, tracking of a randomized ramp and step signal and a sinus signal with the changing frequency.

5.2.3 Results

Figure 5.3 shows the force tracking output of patient P6 as assessed at the beginning and the end of training. In the ramp task (Figure 5.3, above) the patient had difficulties keeping the grip force stable when the signal was leveled. When the target was decreasing he was unable to release the grip completely. After four weeks of training the patient was able to perform the task with much greater accuracy. The tracking error decreased for about three times (from 0.92 to 0.32). The produced output force was smoother with better stability during the constant phases of the signal. The patient also improved the release of the grip and increased the maximal grip strength.

Comparing the results of the step task (Figure 5.3, center) shows that the patient also improved the ability to stabilize the grip force. Overshooting of the target by applying too much force is evident at the beginning of the training, resulting in lower accuracy of tracking (*rrmse*=1.70). At the end of the training the patient was able to track the target with higher precision (*rrmse*=1.41) and produced a smooth response.

The results of the sinus task (Figure 5.3, below) show that the patient was unable to smoothly increase and decrease the grip force at the beginning of training which resulted in more abrupt grip force response with large tracking error (*rrmse*=1.65). The patient could not track the signal during the peak phases of the sinus. After the training the patient considerably improved the performance and reduced the tracking error for more then three times (*rrmse*=0.51).

Comparing the results of all the patients before and after the four-week training showed that the patients improved their overall tracking accuracy. The tasks were performed with much higher precision and the force output was more consistent. Figure 5.4 shows the analysis of the force rate during the sinus tracking. In the beginning of training the patient applied abrupt force when the signal was increasing or decreasing, resulting in irregular and excessive force rate (Figure 5.4, left). The results after the training (Figure 5.4, right) show improved coordination of the grip force with lower deviations from the required force rate.

Figure 5.5 shows daily tracking results as assessed during the four-week training for patient P6. The bar chart on the left shows the maximal grip strength in lateral grip. No significant increase or decrease tendency of the maximal grip force is evident between the beginning and the end of each daily training session. In this patient the maximal grip strength was gradually increasing during the period of training. Figure 5.5 on the right shows the tracking results as obtained in the three training tasks. The results show gradual decrease of the tracking error during the four-week training. Highest improvement in tracking accuracy is evident in the ramp and sinus tasks. The patient improved considerably in the first 10 days while less improvement occurred during the second phase of training. The rapid increase of the error on 19th day of training is likely a result of reduced attention. Table 5.2 shows the improvements in training among the patients as compared between the average scores of the first five and the last five training sessions.

Table 5.2: Improvements in training scores among the patients (* p<0.05, paired samples t-test)

	INCREASE OF FORCE (%)	DECREASE OF TRACKING ERROR (%)		
	TASK 1	*TASK 2*	*TASK 3*	*TASK 4*
P1	6.7*	18.3*	-3.1*	30.6*
P2	17.8*	43.6*	1.0	26.7*
P3	15.3*	20.6*	1.7	39.7*
P4	9.5	53.6*	1.5*	36.1*
P5	141.0*	56.6*	7.9	62.5*
P6	175.0*	46.8*	14.8*	44.6*
P7	42.8*	62.2*	8.9*	68.4*
P8	-19.5	-68.5	-25.8	-77.0
P9	129.3*	43.6*	18.3*	41.4*
P10	-44.4	-2.4	10.6	-34.3

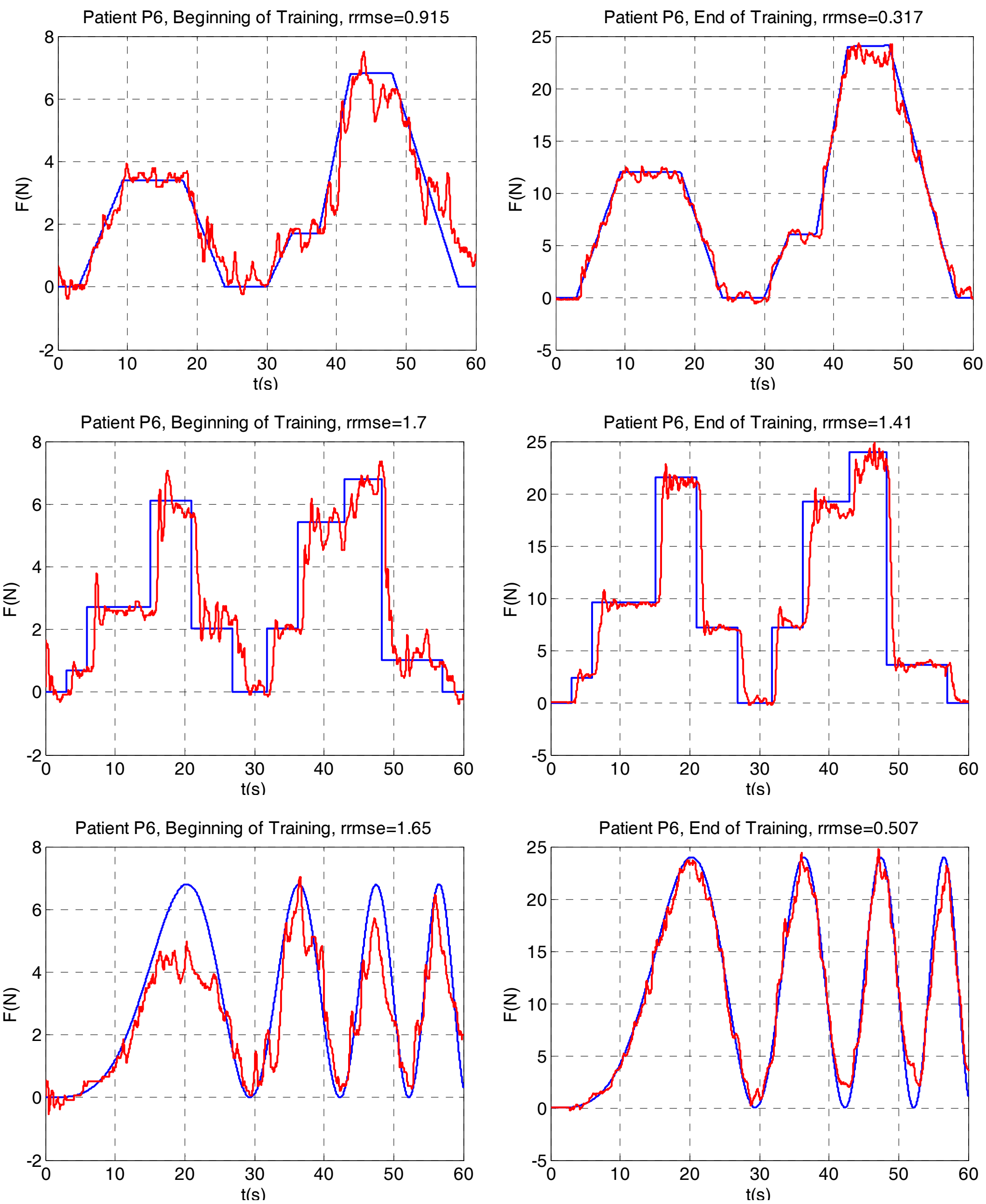

Figure 5.3: The results of the measured force in the three tracking tasks as compared between the beginning and the end of the training period in a patient after stroke. The tracking results show significant improvements in the grip force control following training with the tracking system.

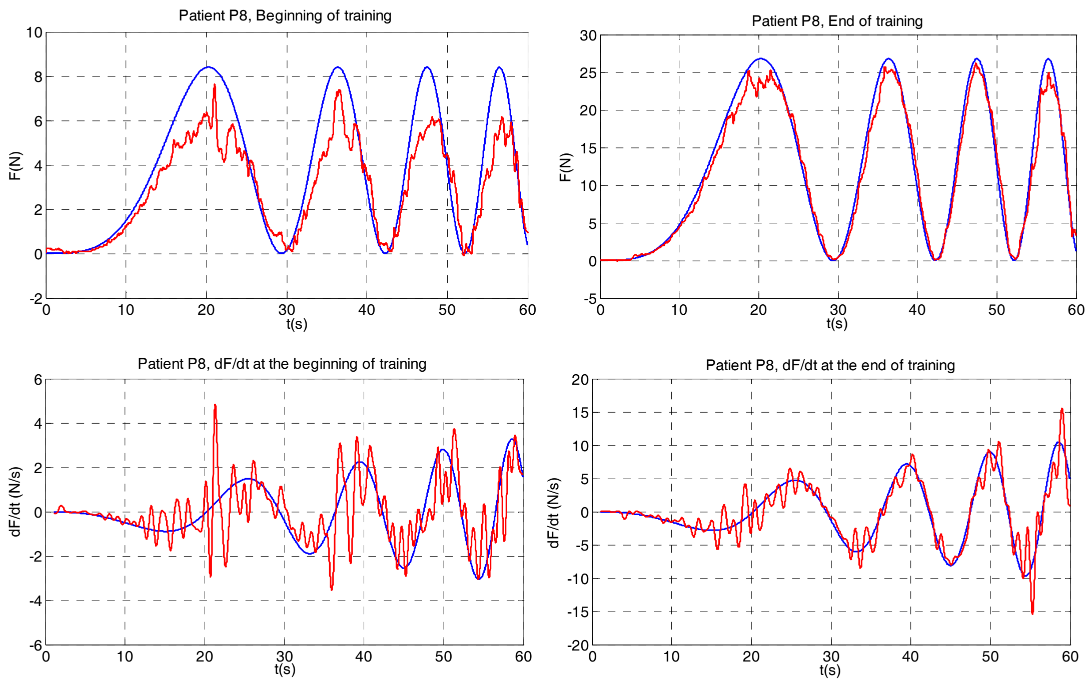

Figure 5.4: Force output (above) and the corresponding force rate (below) at the beginning and the end of training. The patient improved the accuracy of tracking and reduced excessive force rate used before the training.

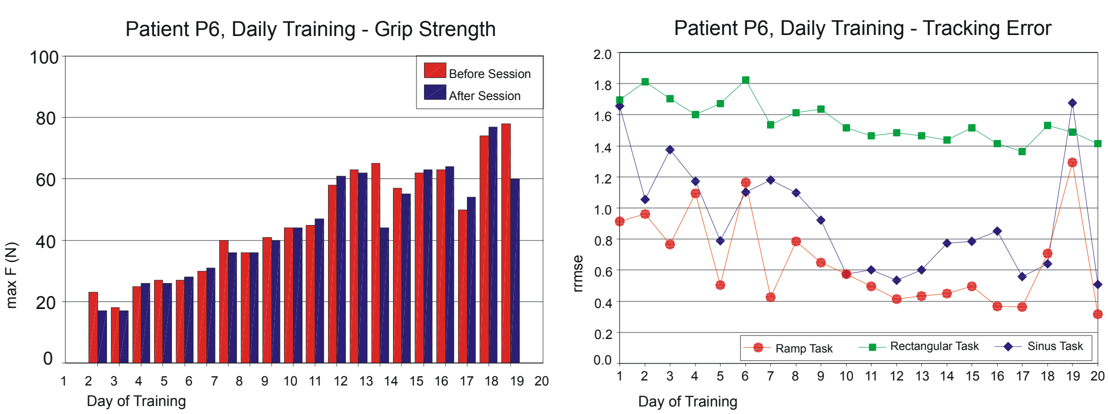

Figure 5.5: Daily training results for the maximal grip force as assessed before and after each session (left) and tracking error in the three tasks (right). The patient increased the grip strength and significantly improved grip force control during the four-week training.

Figure 5.6 shows the tracking results in the ramp task as assessed daily in the affected side (left) and once a week in the unaffected side (right). Only the results of patients who improved significantly during the training are presented. The results of patients P8 and P10 are excluded from Figure 5.6 due to a large variability. Logarithmic regression curve was applied to analyze the trends of the performance in the ramp task for each patient (Figure 5.6, left). Comparing the results of the affected side with the unaffected side shows that all patients considerably reduced their tracking error during the four weeks of training to the levels assessed in their unaffected side. Weekly evaluation was not done for patient P4 due to his inability to perform the grip with the contralateral hand. Only small improvements were evident in patients P1 and P3 who performed the task with high accuracy already at the beginning of the training. The performance of the tracking tasks with the unaffected hand was steady in all patients and the tracking accuracy was much higher as compared to the affected side.

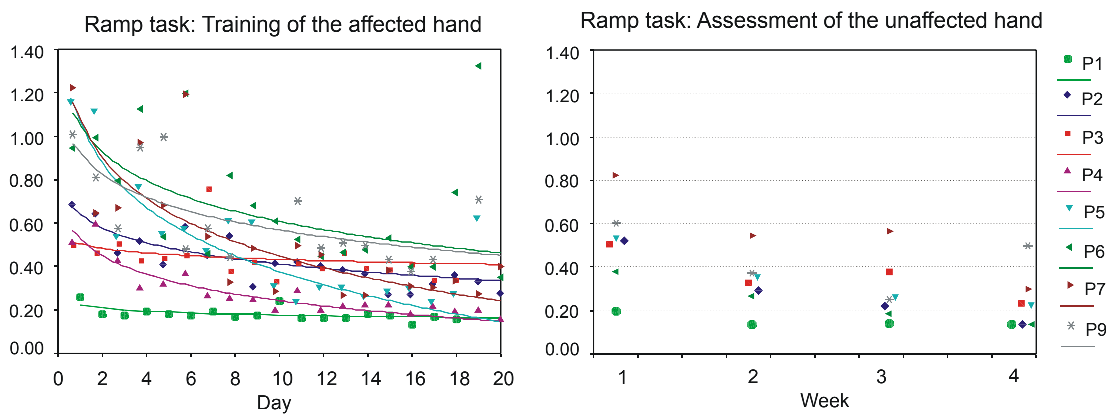

Figure 5.6: The tracking results of daily training in the ramp task showed significant reduction of tracking error in the affected hand (left) as compared to the unaffected hand (right). Logarithmic regression curves were applied to evaluate the average performance trends based on the daily measurements.

Figure 5.7 shows the results of the maximal grip force and the tracking error as assessed in the three training tasks. The average values and standard deviations are compared between the first five and the last five training sessions in each patient. We used the paired samples t-test to test if the difference in the performance between the beginning and the end of training was significant. The results of the first task show that 7 patients improved their maximal grip force during the therapy sessions. Three of the patients (P4, P8, and P10) showed no significant improvements in the maximal grip force due to the large variability among the sessions. The largest increase in grip strength was observed in patients P5 and P6 who showed continuous improvements during the entire period of training. Eight out of ten patients significantly improved their grip force control in the ramp and sinus task while reducing the tracking error. In both tasks, the largest reduction of error was found in patients P5, P7 and P9. The remaining patients demonstrated more advanced performance already at the beginning of training (rrmse<1.0) with lesser improvements during the training period. Patients P8 and P10 showed no consistent results during the entire period of training. In all patients much lower improvements in tracking accuracy were found in the rectangular task where the emphasis was given to the stability of the output force and to the opening and closing of the grip. Relative improvements of the training scores between the beginning and the end of training are presented in Table 5.2.

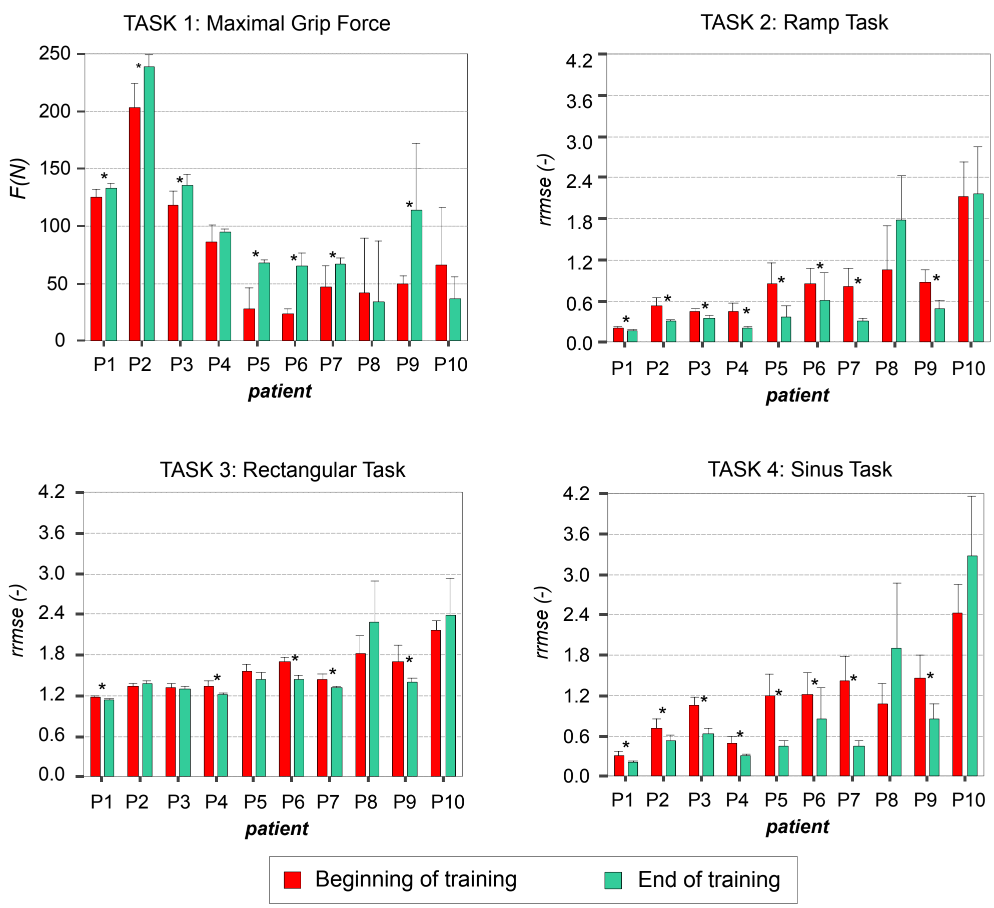

Figure 5.7: The average maximal grip force and the average tracking errors in the three training tasks as obtained for the first and the last five sessions. Significant improvements at the end of training period are indicated for each patient (* p<0.05, paired samples t-test).

5.2.4 Discussion of Results

The results of our study show improvements of the grip force control in 8 out of 10 patients while using the tracking system as supplemental therapy. The difficulty of the tracking tasks was increased by raising the maximal level of the target force for each task if patient's grip strength was increasing during the training program. Seven patients demonstrated increase of the maximal grip strength between the first and the last week of training. The reduction of the tracking error was most evident in the first few sessions. In some patients the tracking error fluctuated during the first two weeks and then the variability was reduced in the second portion of the training period. Most patients reduced the tracking error of their affected side to the performance that was assessed in their unaffected side. In some patients small reduction of tracking error was visible also in the unaffected side which was not trained on a daily basis, suggesting that the patient's overall sensory and motor functions improved during the rehabilitation. Two of the patients (P8 and P10) showed no consistent changes of performances in any of the tasks. Their maximal grip strength remained steady during the training period, while the tracking error fluctuated between sessions. Patient P8 experienced the last stroke 6 years prior to the testing and also showed no observable improvements in other methods of therapy. Patient P10 was the oldest patient in the group (age 79) which could be a possible factor for a slow progress of rehabilitation. The results indicate that the biggest improvement occurred in patients (P5, P7, and P9) who had greatly reduced control of grasping already at the start of the training.

The analysis of the force-time curves showed that the highest reduction of the tracking error occurred in the sinus task which was described as the most difficult task by most patients. In this task the patients improved the overall accuracy of tracking and consequently achieved better grip force control. In the ramp task the patients improved the accuracy and the stability of the output force while reducing the tremor. In the step task the patients mainly reduced overshooting of the target during the abrupt changes between different force levels. In some patients the release of the grip when changing from higher to lower levels of the target was also improved considerably. The ramp and step tasks required high activation of muscles with the aim to maximize patient's motor response. The patients who were unable to reach the 30% level of their maximal grip strength at the beginning of training improved their performance considerably and were able to reach the highest target levels in the last few training sessions.

The results of this investigation show that the isometric grip force training with the proposed tracking method could improve the control of grasping and the grip strength in some patients after stroke. Further study in a larger and more homogenous group of stroke patients is needed to confirm the preliminary findings. Patients participating in such study should be chronic stroke patients (e.g. 6 months after stroke) where it would be easier to evaluate the contributions of the training with the grip force tracking system as compared to the natural reorganization occurring in the central nervous system in the first few months after stroke. The patients should also be scored with one of the standardized tests used in clinical evaluation (e.g. Fugl-Meyer motor assessment test) to follow the progress of such therapy.

6 Virtual Environment for Assessment and Rehabilitation

In this chapter we present a new approach to multi-fingered grasping in virtual environment using an isometric input device. The isometric 3By6 Finger Device was designed to simultaneously assess forces applied by the thumb, index, and middle finger [64]. The measured forces are mapped to a virtual object which dynamically corresponds to the resulting force and torque. Grasping in the virtual environment was described by the mathematical model adopted from the analysis of multi-fingered robot hands presented by Murray and colleagues [85]. Sense of haptic feedback is achieved through visual cues from the environment and tactile feedback experienced at the fingertips during the application of force. In this chapter we present the realization of multi-fingered grasping using the pseudo-haptic feedback and the mathematical model of the virtual environment. The proposed method was used to design four VR tasks aimed for rehabilitation of hand function in stroke patients. The tasks include opening of a safe, filling and pouring water from a glass, training of muscle strength with an elastic torus and a force tracking task. The training tasks were designed to train patient's grip force coordination and increase muscle strength through repetitive exercises. In this dissertation we present preliminary results obtained in a small group of healthy subjects and in one post-stroke patient.

6.1 Grasping and Manipulation in Virtual Reality

Interaction with objects in virtual environment through grasping and manipulation is an important feature of the future virtual reality (VR) simulations [7]. The interaction with virtual objects is possible by pushing, pulling or grasping an object to change its position, orientation or shape (e.g. deformation). The manipulation of objects can be performed using standard computer interface devices (e.g. a mouse, joystick), instrumented gloves, or more complex haptic interfaces.

Instrumented gloves are most frequently used for multi-fingered interaction with the virtual environment. The gloves are equipped with optical or resistive sensors which provide data on the finger joint angles. Using direct kinematics, posture of the fingers can be accurately displayed and the position of the fingertips is determined to allow interaction with objects [8]. When using VR gloves, the user has to depend only on visual feedback to obtain information on the position of the fingers in space and the state of the manipulated object. The information on the contacts is presented only by visual cues making a precise manipulation more difficult. During manipulation in real environment, proprioceptive and tactile feedback is received through human sensing system providing information on forces and collisions with objects [68]. The level of VR interaction can be increased by using a real object for manipulation while interacting with a virtual object of similar physical properties (e.g. shape, size). The objects can be equipped with different sensors (e.g. motion tracking sensor, accelerometer) in order to present the movement of the virtual object in more realistic manner. In such hybrid environments the performance is superior to the virtual-only environments and closer to real life performance [7].

The interaction with the instrumented gloves can be further enhanced by using a haptic interface which provides force feedback to the user in addition to the visual feedback provided by the VR application. Haptic devices were originally developed for telemanipulation where a master-slave system was used to manipulate distant objects in hazardous environments. Haptic feedback was later added to the existing telemanipulation systems to achieve better control for the operator. For the interaction in virtual environment several haptic devices have been developed. The most widely used haptic device is PHANToM (SensAble Technologies[2], Woburn, MA) which allows interaction with virtual objects through one point of contact at the fingertip. Hirota and colleagues [41] and McKnight and colleagues [78] used two or three PHANToM devices for multi-fingered manipulation of virtual objects. For more realistic manipulation, whole-hand haptic devices are used. Whole-hand haptic systems for multi-fingered manipulation must offer high level of mobility of the fingers and haptic feedback in different areas of the hand [110]. Bouzit and colleagues [9] presented Rutgers Master II system with pneumatic-based actuator platform located at the palm which provides force feedback to four fingers. The system was successfully applied in VR training of stroke patients [48]. A different approach is used with the exoskeleton system CyberGrasp [120] which is worn in combination with the instrumented glove CyberGlove (Immersion Corporation, San Jose, CA). The glove measures joint angles while the exoskeleton provides force feedback to the fingertips. Kawasaki and colleagues [55] proposed a robotic haptic device where the fingertips of the human operator are attached to a five-fingered robotic hand. One of the drawbacks of the whole-hand haptic devices is the complexity of the control algorithms [55], limited degrees of freedom, and small feedback forces provided by such systems (e.g. Rutgers Master II up to 16 N). High costs and safety issues of haptic devices limit their use in rehabilitation environment.

Haptic feedback can be partially replaced by a low-cost alternative such as visual feedback where the haptic information is provided indirectly through visual or other cues [7, 96]. This approach implements incomplete haptic feedback which is also described as *pseudo-haptic feedback* [65]. Compared to VR gloves, where the motion of the fingers is fully unconstrained, pseudo-haptic devices constrain the motion while measuring the force applied to the force sensing elements. The tactile feedback is provided through fingertips when a force is applied to the device. If an increase of the force is required by the VR task, the user will apply higher fingertip force and consequently feel larger resistance due to the motion constraints at the fingertips [7, 65, 96]. Casiez and colleagues [14] presented a three-degree of freedom haptic device DigiHaptic which allows *isotonic* and *isometric mode* of operation. In isotonic mode with force feedback the device is controlled only by a small movement of three fingers placed on the control wheels which operate as haptic input. In isometric mode, where the movement of the fingers is restricted, the applied force at the control wheels is measured to allow VR interaction.

Input devices can be implemented either for rate or position control to interact with the virtual environment. When employing the rate control, the velocity of the object is proportional to exerted force. In position control the displacement is directly proportional to the force. Isometric devices are more commonly used in connection with the rate control. Using the pseudo-haptic approach, the position control mode can also be applied to simulate experience of compliance [14, 65]. Lee and colleagues [66] reported that isometric devices provide better control in positional tracking in VR. Zhai and colleagues [120] on the other hand found equal performance characteristics in both, the isometric and isotonic control mode.

An advantage of the isometric input devices intended for rehabilitation is their low fatigue factor which allows prolonged use in the virtual environment as compared to the isotonic devices [14]. Isometric devices have no moving parts, making the device much safer to use with patients. The cost of isometric devices is mainly determined by the price of the force sensing system.

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[2] http://www.sensable.com

6.2 Forces and Torques in Multi-Fingered Grasping

In multi-fingered grasping each finger can be described as an independent kinematic chain with multiple degrees of freedom [84]. At each point of contact additional degrees of freedom exist (i.e. *contact degrees of freedom*), defining the motion between the fingertip and the object. The contact degrees of freedom are passive and depend on the implemented contact model. A contact between the finger and the object surface can be mathematically described as a mapping between the forces exerted by the finger and the resultant wrench (i.e. vector of forces and torques) with regard to a reference point on the object (e.g. center of mass) [85]. The contact can be modeled as: (1) *frictionless point contact*, (2) *point contact with friction*, and (3) *soft-finger contact*. The model of the contact is defined by the number of forces and torques that can be applied by the fingertip to a rigid surface. A frictionless point of contact exists where there is no (or very low) friction between the fingertip and the object. The finger can exert forces only along the normal direction. Such contact is idealized and less significant for practical applications. A point contact with friction is adopted when there is friction between the fingertip and the object surface. The forces can be applied in any direction within the *friction cone* (FC) (Figure 6.1.a). The friction cone describes the Coulomb friction model in three-dimensional space where the two tangential forces are proportional to the normal force as the function of the friction coefficient [56]. The third type of contact is a soft-finger contact where in addition to all three forces, a torque around the normal direction can be exerted (Figure 6.1.b). Soft-finger contact is the most realistic of the three contact models [85].

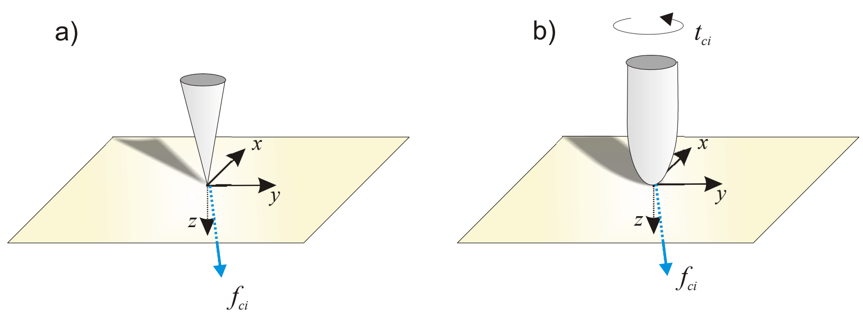

Figure 6.1: Contact models for multi-fingered grasping: (a) point contact with friction, (b) soft-finger contact.

In multi-fingered grip several fingertips are simultaneously in contact with the object surface exerting forces and torques at each contact point. To describe the total effect of multiple contacts, a mapping between the fingertip forces and the resultant wrench on the object with regard to its center of mass (COM) is needed. Figure 6.2 shows grasping of an object with multiple fingertips. The location of the i-th contact point is defined by the coordinate system C_i with the z-axis pointing inwards to the object surface. The position and orientation of the contact coordinate system are described by the vector $\boldsymbol{p}_{oci} \in \Re^3$ and the rotational matrix $\boldsymbol{R}_{oci} \in \Re^{3\times3}$, respectively. In our model we assume that the location of the fingers, when in contact with the object, is fixed relatively to its COM.

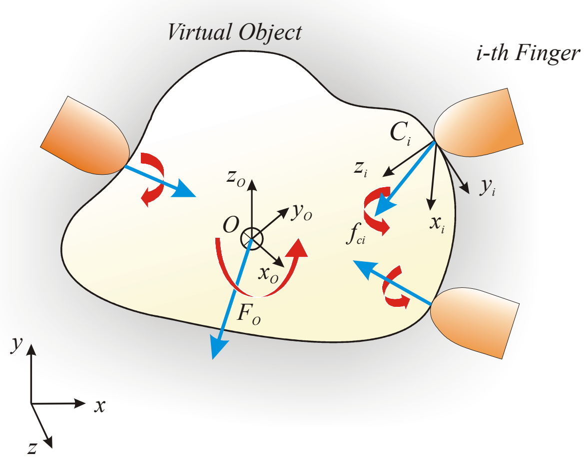

Figure 6.2: Forces and torques in multi-fingered grasping of a rigid object.

The contact is kinematically described by the wrench basis $\boldsymbol{B}_{Ci} \in \Re^{6\times p}$ which defines the number of degrees of freedom p in which the object is fully constrained. Depending on the contact model, the fingertip can apply forces and torques comprised in the vector $\boldsymbol{f}_{Ci} \in \Re^{p}$. In case of a point contact with friction, the contact wrench with respect to the corresponding wrench basis is described as follows:

$$F_{C_i} = B_{C_i} \cdot f_{C_i} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}^{\mathrm{T}} \cdot f_{C_i} \tag{6.1}$$

The components of the force $\boldsymbol{f}_{Ci}$ must lie within the friction cone of the friction coefficient μ defined as:

$$FC_{C_i} = \left\{ f \in \Re^3 : \sqrt{f_x^2 + f_y^2} \leq \mu \cdot f_z, f_z \geq 0 \right\} \tag{6.2}$$

In case of a soft-finger contact, the contact wrench in addition to all three forces includes a torque around the normal direction:

$$F_{C_i} = B_{C_i} \cdot f_{C_i} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{\mathrm{T}} \cdot f_{C_i} \tag{6.3}$$

The friction cone of the soft-finger contact incorporates torsional friction coefficient γ and is described as follows:

$$FC_{C_i} = \left\{ f \in \Re^3 : \sqrt{f_x^2 + f_y^2} \le \mu \cdot f_z , f_z \ge 0 , \left| t_z \le \gamma \cdot f_z \right| \right\} \tag{6.4}$$

To describe the effect of each contact on the object, the contact wrench $\boldsymbol{f_{Ci}}$ is transformed to the object coordinate system using the contact map $\boldsymbol{G_i} \in \Re^{6\times p}$:

$$F_{OC_i} = \begin{bmatrix} R_{OC_i} & 0 \\ P_{OC_i} & R_{OC_i} \end{bmatrix} \cdot B_{C_i} \cdot f_{C_i} = G_i \cdot f_{C_i} \tag{6.5}$$

The matrix $\boldsymbol{R_{oci}}$ denotes the orientation matrix of the contact coordinate system. The matrix $\boldsymbol{P_{OCi}}$ represents the antisymmetrical matrix of the vector $\boldsymbol{p_{OCi}}$ describing the position of the contact point with regard to the COM.

In case of multiple (k) contacts with the object, the total wrench on the object is defined by a linear transformation of all contact wrenches:

$$F_O = G_1 \cdot f_{C_1} + G_2 \cdot f_{C_2} + \ldots + G_k \cdot f_{C_k} = \begin{bmatrix} G_1 & \cdots & G_k \end{bmatrix} \cdot \begin{bmatrix} f_{C_1} & \cdots & f_{C_k} \end{bmatrix}^{\mathrm{T}} \tag{6.6}$$

Finally, the contact maps $\boldsymbol{G_i}$ of each contact point are collected in the grasp map, defined as the matrix $\boldsymbol{G} \in \Re^{6\times kp}$:

$$F_O = G \cdot f_C \qquad , f_C \in FC \tag{6.7}$$

The equation (6.7) defines the transformation of the matrix of the fingertip forces $\boldsymbol{f_C} \in \Re^{kp}$, which lie within the friction cone of the contact model, into the resulting force and torque on the object defined as the wrench vector $\boldsymbol{F_O} \in \Re^6$.

6.3 Mathematical Model of Virtual Environment

The motion response of a rigid body as a result of external forces is described by a mathematical model of body dynamics. The location of the object in space is defined by the position and orientation of body coordinate system attached to the object in the center of mass. The position and orientation can be described by three Cartesian coordinates (x, y, z) and roll-pitch-yaw parameters (R, P, Y), respectively. The six parameters fully describe object pose defined by the vector $\boldsymbol{x} \in \Re^6$.

When an external force is applied to a rigid body, the body starts accelerating due to an imbalance of forces (Newton's Law). As a result, translational and/or rotational movement of the object is initiated. The velocity of the object is defined by the velocity vector $\dot{x} \in \Re^6$ while the acceleration is denoted with $\ddot{x} \in \Re^6$. The external forces are described with the wrench $\boldsymbol{F_O} \in \Re^6$, consisting of three force and three torque components. The resulting motion depends on object mass, inertia parameters, friction, gravity and any other external forces. The object accelerates until the external forces are present or until the forces acting on the object are not in balance. In case of multi-fingered grasping the fingertips in contact contribute to the total force on the object as described by equation (6.6).

For the simulation of grasping using an isometric input device, the relative position of the contact points is fixed to the object surface. Dynamic behavior of the object depends on the resulting wrench at the center of mass. The virtual object is in its center of mass suspended on virtual springs with friction in all six degrees of freedom (i.e. three translations and three rotations) as shown in Figure 6.3. By adjusting the stiffness and friction parameters, dynamic behavior of the object is fully controllable, allowing in this way very high flexibility of the VR environment. With high stiffness of a virtual spring and sufficient friction, the speed of movement in the selected direction can be directly proportional to the input force. With low stiffness of the spring and low friction, the object will behave as if it was suspended on a real spring. The coefficients can be adjusted according to the application. The number of active degrees of freedom can be limited to restrict the movement in particular directions (e.g. a knob must only rotate around its main axis; other five degrees of freedom are constrained). The proposed dynamic model incorporates object mass, inertia, geometry (e.g. shape, size) and the location of COM with regard to the global coordinate system. The environmental variables include stiffness of the virtual springs and the corresponding viscous friction.

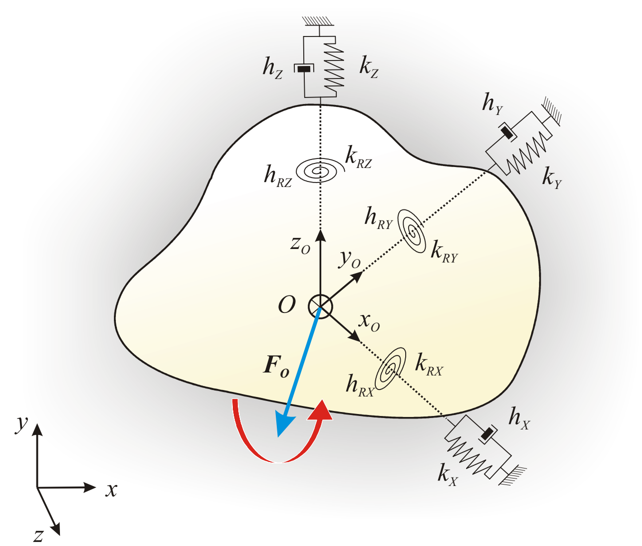

Figure 6.3: Model of object dynamics for isometric multi-fingered grasping implements virtual springs with stiffness (k_i) and friction (h_i) in all six degrees of freedom.

To describe dynamics of the object shown in Figure 6.3, we use Newton-Euler equations written in the matrix form [98]:

$$M \cdot \ddot{x} + C \cdot \dot{x} + N \cdot x + g = F_O \qquad (6.8)$$

In equation (6.8) $\boldsymbol{x} \in \Re^6$ represents the vector of local coordinates describing the object pose, the matrix $\boldsymbol{M} \in \Re^{6\times6}$ is the inertia matrix consisting of object mass and inertia parameters, $\boldsymbol{C} \in \Re^{6\times6}$ is a diagonal matrix of friction coefficients, $\boldsymbol{N} \in \Re^{6\times6}$ is a diagonal matrix of stiffness coefficients of virtual springs and $\boldsymbol{g} \in \Re^6$ is the gravity vector. In our environment the gravity was excluded from the model because it would be too difficult to compensate using an isometric device. $\boldsymbol{F_O}$ is the total wrench on the object resulting from the fingertip forces and is obtained from the equation (6.7).

Next the acceleration vector is expressed from the equation (6.8):

$$\ddot{x} = M^{-1}(F_O - C \cdot \dot{x} - N \cdot x) \qquad (6.9)$$

To obtain the position and orientation of the object in local coordinates, Euler integration algorithm [67] was applied to the equation (6.9):

$$x = \iint \ddot{x} = \iint M^{-1}(F_O - C \cdot \dot{x} - N \cdot x) \qquad (6.10)$$

Equation (6.10) describes dynamic behavior of a virtual object in space and time resulting from the total wrench applied to the object, its physical properties and given environmental variables.

The above equations apply to dynamic simulation of rigid objects. In case of a deformable object, the dynamics model can be derived from parametrically defined rigid primitives that deform kinematically with the applied force (e.g. a cylinder deforms by the change of its radius and length) [82]. Deformable objects can be modeled by global deformations which affect the global geometry of the object (e.g. bends, twists, and shears). The dynamics of such models is described by the six degrees of freedom of a rigid-body motion and the global and local deformation parameters. The deformation parameters directly correspond to forces and torques applied to the object. In multi-fingered grasping of deformable objects *internal wrench* resulting from the fingertips affects the global deformations while the *total wrench* on the object ($\boldsymbol{F_O}$) affects the motion in the same way as in the case of a rigid object. The internal forces are defined as a set of contact forces for a current grip configuration which results in no net force on the object (i.e. no motion is initiated) [85]. Mathematically, the internal forces represent the homogenous solution of equation (6.7) defined as the null space of the grasp map $\boldsymbol{G}$:

$$F_O = G \cdot f_C = 0 \qquad , f_C \in null(G) \qquad (6.11)$$

In case of opposing fingertips in a plane, calculating the internal forces can be simplified. The global deformation parameter is described as a function of the difference between the sum of the normal fingertip forces (with regard to the center of mass) and the total force which affects the object motion.

6.4 3By6 Finger Device

The isometric 3By6 Finger Device was designed to simultaneously measure forces and torques applied by the thumb, index, and middle finger [64]. The device consists of three 3D force/torque measuring sensors (50M31A-I25; JR3, Inc., Woodland, USA) located on the outer side of the hand (Figure 6.4). The sensors are mounted on the aluminum construction, which provides firm support for the sensors during the measurement. The measurement range of the sensors is 150 N for the lateral forces and 300 N in the axial direction with the torque range of 8 Nm. The approximate outer measures of the finger device are 220x100x160 mm and total weight is 1.8 kg. During the measurement the hand is positioned between the thumb sensor and the two sensors for the index and middle finger. Finger supports are used to fix the two fingers and the thumb in the correct position and to allow transfer of forces and torques to the sensors. The finger supports made of plexi-glass allow the transfer of the fingertip force to the sensor. The shape of the finger support is ergonomically designed without any sharp edges. The fingers are attached to the support using Velcro straps. Additionally, finger pads made of neoprene material can be used to fill the space between the finger and the finger support. The distance between the thumb and the two fingers is 65 mm to provide comfortable position of the hand. Forearm support can be used to stabilize patient's arm and to keep neutral position of the wrist. The device can be applied either for the left or the right hand measurement by changing the orientation of the sensor platform by 180˚. The data acquisition from the three sensors is performed through a PCI receiver/processor board with the sampling frequency up to 500 Hz. The data are filtered in real time using an on-board integrated filter with the cut-off frequency of 32.25 Hz and the delay of approximately 32 ms.

The 3By6 Finger Device was originally designed and is used for the assessment of upper extremity in stroke patients within European Union (EU) funded project Alladin[3] under the 6th Framework Program (Contract No.: IST-2002-507424). Larger scale study of isometric measurements is underway in parallel to obtaining clinical outcome measures of patients during the process of rehabilitation. The aim of the project is to develop user-friendly

[3] http://www.alladin-ehealth.org

natural language based decision support software for neuro-rehabilitation, which could predict the functional recovery of stroke patients.

When using the finger device, the movement of the hand and fingers is fully constrained allowing the virtual environment to simulate grasping through the fingertip forces instead of using finger positions. Based on the given task, the user exerts forces and torques which would normally be applied during grasping and manipulation in real environment resulting in realistic response of a virtual object. The tactile feedback received from the fingertips while using 3By6 Finger Device is similar to the tactile sensation experienced when grasping real objects. The feedback on the position and velocity of the fingers is replaced by the visual feedback from the VR application.

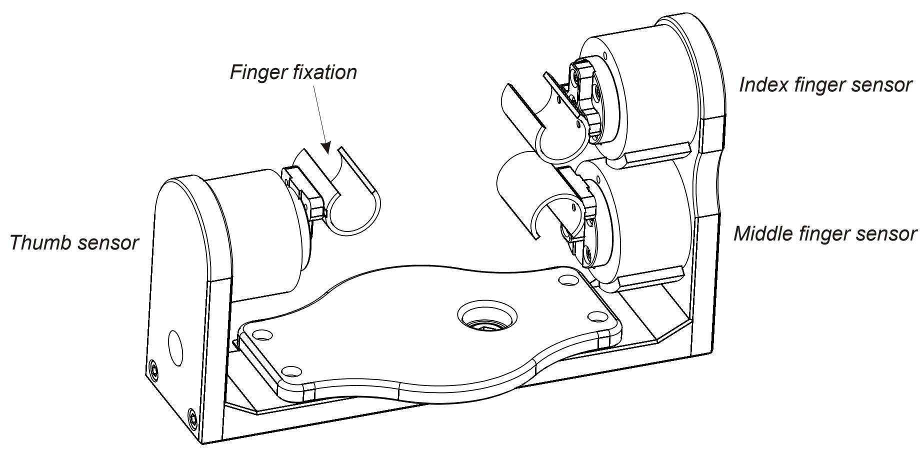

Figure 6.4: Isometric 3By6 Finger Device allows measurement of forces and torques applied by the thumb, index and middle finger. The device allows three-fingered grasping and manipulation of virtual objects in a synthetic environment.

6.5 Virtual Environment for Multi-Fingered Grasping

6.5.1 MAVERIK

The visualization of the virtual environment was achieved using open source VR system MAVERIK (Advanced Interfaces Group, School of Computer Science, University of Manchester, UK) which is based on OpenGL graphics library. The engine provides a set of basic functions for constructing virtual environments using *C* computer language. A virtual environment is built by adding different objects into the scene, either default primitives (e.g. polygons, spheres, boxes, and others) or VRML objects created with any 3D design software. In MAVERIK an object is described by a class consisting of object geometrical properties, color, material, and the corresponding homogenous matrix defining object position and orientation. The calculations needed to update the object parameters based on the force input are performed inside the rendering loop. The rendering loop allows data acquisition and visualization update with the frequency of 100 Hz.

MAVERIK was selected because of its high-performance rendering, customized representation of environments, high-flexibility of object interaction (e.g. collision detection) and the ability to construct new objects with flexible physical properties (e.g. deformable surfaces) [44]. Two additional *C*-libraries `grasping.h` and `bodydynamics.h` were programmed to include the mathematical models of multi-fingered grasping and object dynamics independent of the visualization engine.

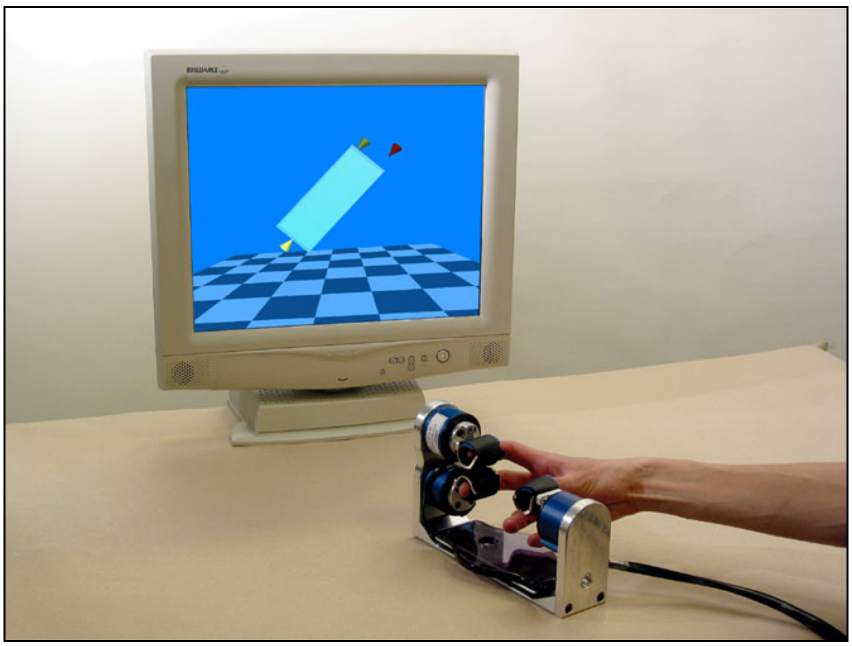

Figure 6.5: Isometric 3By6 Finger Device and the virtual environment for multi-fingered grasping and manipulation.

6.5.2 Realization of VR environment

The multi-fingered grasping is implemented in MAVERIK by first defining dynamics parameters (e.g. mass, inertia, compliance of virtual springs and friction for each degree of freedom) of the manipulated object. The defined structure is linked with the MAVERIK object class. The parameters can be defined inside the code or loaded from an external initialization file with the application start. Next, the number of fingers and their position and orientation with respect to the object coordinate system is defined. A point contact with friction or soft-finger contact can be used. The parameters defining the contacts can also be loaded from an external initialization file. The fingers are rendered as cone-shaped objects. The pose (i.e. position and orientation) of each contact relatively to the object coordinate system is predefined with the object geometry. The direction of the finger contact (z-axis) is set along the main axis of the cone. A threshold force must be exceeded for the virtual finger to come in contact with the object. When the force is applied, the virtual finger is moved along its main axis proportionally until the collision with the object is detected. The default collision detection, already implemented in MAVERIK, was used. If the force of the finger is below the threshold, the contact is inactive and does not affect the movement of the object. When the threshold is exceeded and the contact with the object is made, the color of the virtual finger is changed from red to green, signaling the activation of contact.

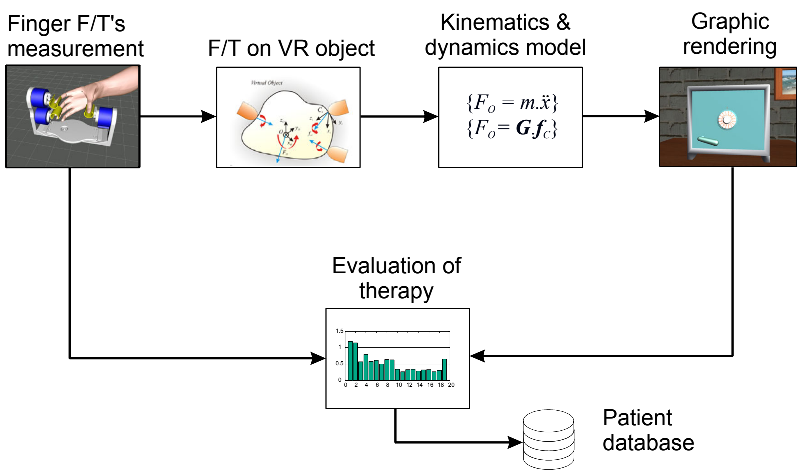

Figure 6.6: Block scheme of the virtual environment for multi-fingered grasping aimed at the rehabilitation of hand function.

In each rendering loop the object position is updated with the frequency of 100 Hz based on the dynamics model of the environment and the measured fingertip forces. The total wrench resulting from the fingertip forces is calculated from the equation (6.7). Using the equation (6.9), acceleration of the object is determined from all the forces acting on the object (e.g. grip force, frictional force, elastic force of the virtual springs). Next, Euler integration algorithm is applied on the equation (6.10) to acquire new position and orientation of the object. The virtual scene is updated at the end of the rendering loop according to the new calculated values. In each step the fingertip forces and torques, resulting wrench, object position and orientation, velocity and acceleration are stored in a binary file. Figure 6.6 shows the basic structure of the presented VR application for multi-fingered grasping with 3By6 Finger Device.

Figure 6.7 shows manipulation of a virtual box using 3By6 Finger Device and developed VR application. With one finger in contact, the object can be pushed into direction of the applied fingertip force. The object is grasped when two or three fingers in opposition are in contact with the object. Grasped object can be moved in either direction or rotated around its coordinate axes. Dynamic response of the object is controlled by the stiffness of the virtual springs and friction in each degree of freedom. The movement can be also restricted in specific directions (e.g. object movement can be restricted to the vertical plane).

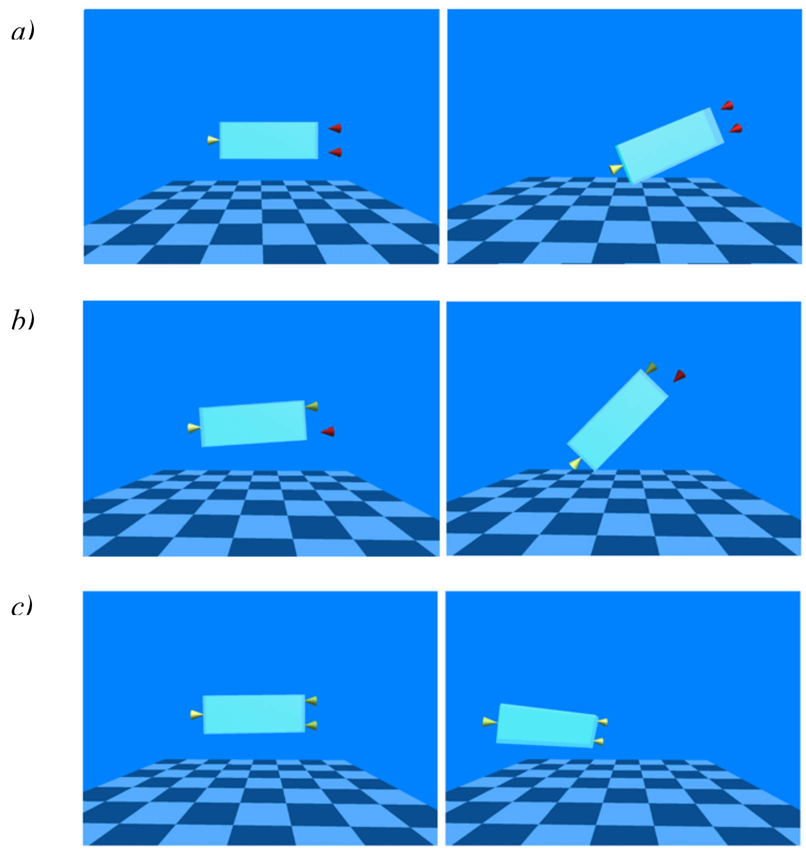

Figure 6.7: Multi-fingered isometric finger device allows several ways of interaction with virtual objects: (a) pushing the object with one finger, (b) rotating the object with two fingers, and (c) moving the object with three fingers.

6.6 Training Tasks

Four VR tasks aimed for the rehabilitation of hand function (e.g. in stroke patients) were designed using the proposed modeling concept. The tasks include opening of a safe, filling and pouring water from a glass, training of muscle strength with an elastic torus and grip force tracking task. Based on the VR rehabilitation scheme shown in Figure 3.1 (page 38), the first three tasks are aimed to increase the grip force coordination and grip strength while the tracking task is intended for the assessment of the rehabilitation progress. The tasks are aimed to assess and promote grip force control and grip strength through functional activity, while being fun and motivating for the patient.

6.6.1 Task #1: Open the Safe

The first task requires the patient to unlock the door of a safe by finding the correct combination code (Figure 6.8). The combination code is presented on the screen and the user has to sequentially rotate the knob to the corresponding values. The code is randomly generated in each session. The knob is marked with numbers from *1* to *7* on the right side and letters from *A* to *G* on the left side. The neutral position of the knob is denoted with *0*. When the knob is turned to the correct angle, the current symbol of the combination code disappears and the next symbol in the combination needs to be found. To rotate the knob, the user has to first grasp the knob and then apply axial torque to turn it to the correct orientation. The knob is connected to a virtual spring and friction which define dynamic behavior during rotation. The task is completed when the combination code is cracked and the safe opens. The difficulty of the task can be modified by changing the length of the code and the maximal force needed to rotate the knob for one revolution. During the performance of the task the forces and torques of the three fingers, total wrench on the object, orientation of the knob and the reference values of the given combination code are stored.

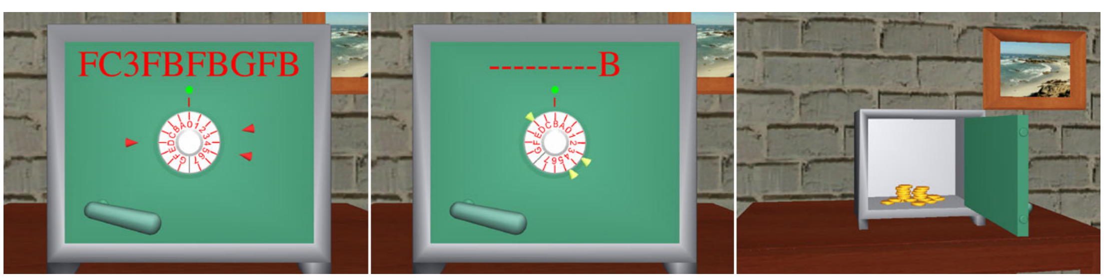

Figure 6.8: In "Open the safe" task a knob with numbers and letters has to be sequentially rotated to find the presented combination. The task is aimed to improve grip force control.

6.6.2 Task #2: Fill the Jar

In the second task the patient has to fill an empty jar with water (Figure 6.9). The patient needs to grasp the glass, transport it to the water tap to fill it up, and then pour the water into the jar. The glass is grasped by applying opposing force with two or three fingers. The glass can be moved in either direction by applying appropriate resulting force of all fingers into the corresponding direction while the object is securely grasped. The movement is restricted to the vertical plane and the rotation is allowed only around the *z*-axis. Basic collision detection with bounding boxes is implemented. When the glass is moved under the water flow, another collision detection algorithm detects the collision between the ray of the water flow and the top of the glass to appropriately increase the water level. The dynamics of water inside the glass is modeled by a cone shaped body which corresponds to tilting. The model includes the changing mass of the glass which corresponds to the volume of water. If the water is spilled over the edge, a water flow is rendered and the amount of water is reduced accordingly. If the water flow from the glass penetrates the top of the jar, the jar is filled by the same amount of water. The task is completed successfully when the jar is filled to the level marked with a red line on the side of the jar (Figure 6.9). The difficulty of the task can be adjusted by changing dynamics parameters of the environment and by setting different target levels for the jar.

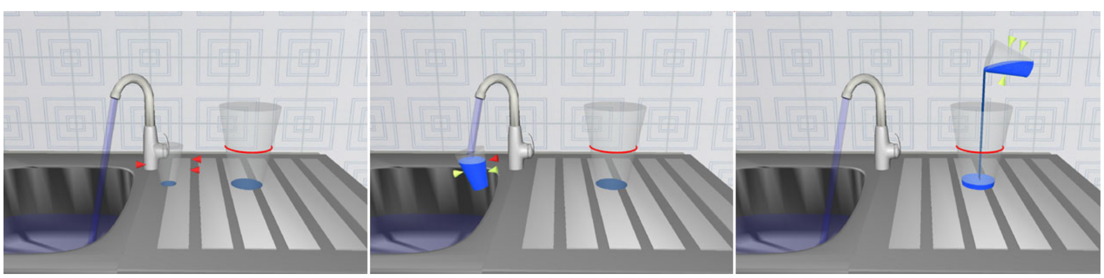

Figure 6.9: In "Fill the jar" task the user has to grasp and use the glass of water to fill up the jar to the marked height. The task is aimed to improve finger coordination.

6.6.3 Task #3: Elastic Torus

The third task is aimed to increase the grip strength by repetitive exercises of hand opening and closing (Figure 6.10). The patient is presented with a deformable torus with geometry and dynamic model corresponding to the grasping force between the fingers in contact. The position of the torus is fixed in space whereas the stiffness can be adjusted to individual abilities. Global deformation modeling [82] was used to model the elastic torus in our virtual environment. During training the patient is guided through the task by color cues to correctly perform the exercises. When the torus is compressed beyond the required degree, the color is changed from dark blue to purple, indicating closure of the grip. After a specific time, the color of the torus is changed back to dark blue, indicating the release of the grip. When the grip is completely opened (i.e. no compression force is exerted on the torus), the color is changed back to purple. The counter on the screen indicates the number of successfully performed sequences. The difficulty of the task can be adjusted by changing the stiffness of the torus, selecting the required number of cycles to complete the task and the time delay between each sequence.

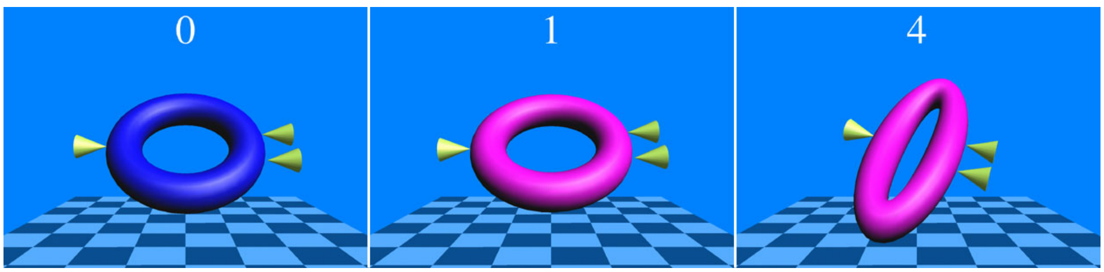

Figure 6.10: In "Elastic torus" task the user has to sequentially open and close the grip according to the changing color of the torus. The task is aimed to improve grip strength by repetitive exercises.

6.6.4 Task #4: Tracking

The fourth task is primarily intended for the assessment of the overall training process. The patient is required to track a changing target by applying appropriate grip force with the coordinated control of the three fingers. The target signal is presented with a small blue ring moving vertically in the center of the screen while the applied force is indicated with a red semi-transparent sphere (Figure 6.11). When the grip force is exerted, the red sphere moves upwards and when the grip is released, the sphere moves to the initial position. While the sphere is inside the target, the color of the sphere is changed from red to green. The past values of the two signals are presented as two time-varying trails (in blue and red color). The aim of the task is to continuously track the position of the target by dynamically adapting the grip force. The abstract nature of the tracking task was chosen with the intention to minimize the stress on patient's cognitive abilities in order to emphasize the motor control rather than visual and cognitive perception.

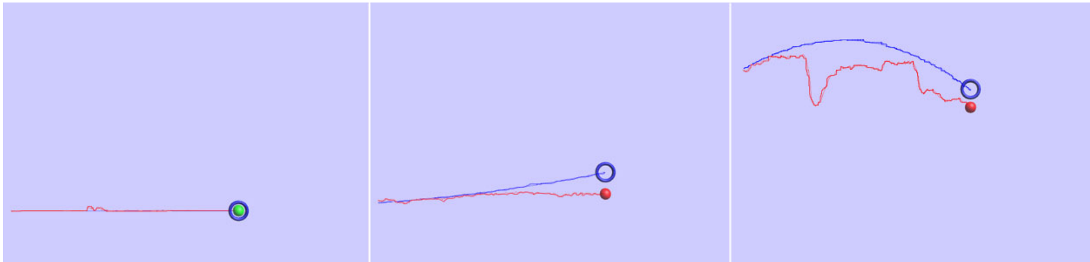

Figure 6.11: Grip force tracking task is used for the assessment of the training progress. Different target signals can be used to assess patient's grip force control, response time, muscle fatigue.

6.6.5 Application for VR training

A cover application for VR training was developed in Microsoft Visual Studio (Figure 6.12). The application allows execution of different training tasks and patient's data management. Three different difficulty levels were created for each of the four VR tasks to accustom patients with different functional abilities. The cover application implements MS Access database to store data acquired during the training. The software allows the therapist to add and edit patient records while all the training data is automatically stored. For each training session a binary file containing force and torque data of the fingertips and different data describing task dynamics is saved. The results of each task (e.g. time needed to complete the task) and session related parameters (e.g. date, time, hand trained) are stored directly into the database. The cover application also provides the therapist and patient with a bar chart of the average scores to follow the progress of the VR training (Figure 6.12).

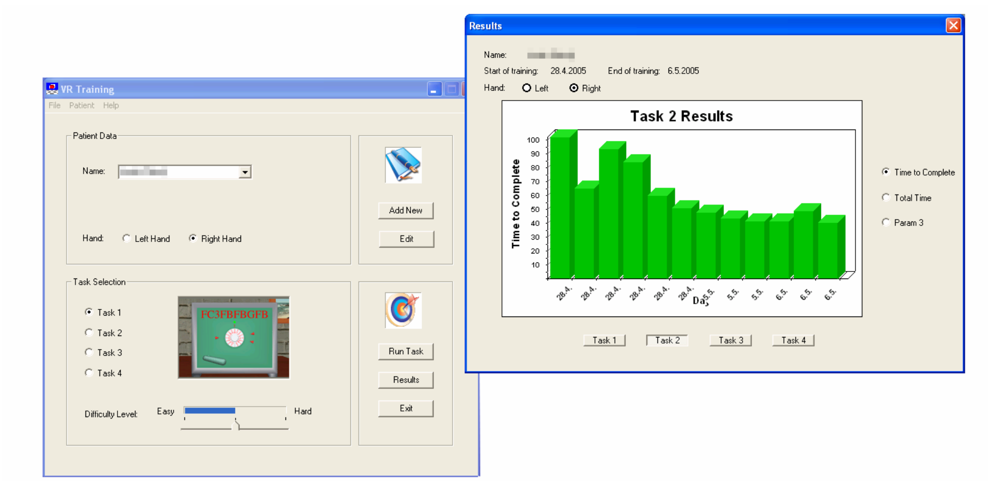

Figure 6.12: Cover application of VR rehabilitation system.

6.7 Results in Healthy Subjects

Preliminary measurements with the VR training system were done in 5 healthy subjects (mean age: 26.8 (SD 2.3) years) to obtain more information on performance of the tasks. The subjects performed each training task three times in four separate sessions using the dominant hand. In this chapter we present some of the results obtained in the preliminary assessment.

6.7.1 Open the Safe

Figure 6.13 shows the orientation of the safe knob while opening the safe. The reference line represents the required orientation of the knob for a particular safe combination (e.g. rotation for -22.5° corresponds to the letter "A"). A symbol in the combination code is cracked if the knob is kept within the selected tolerance limit (±5°) for 2 seconds. The orientation tolerance, delay time and length of the code depend on the selected difficulty level of the task.

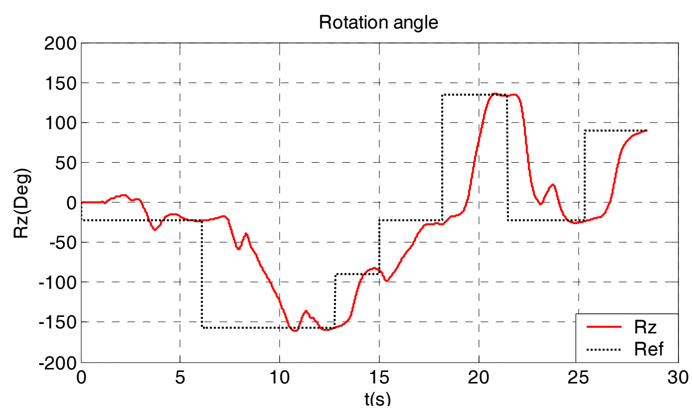

Figure 6.13: Rotation angle of the knob during the safe opening. The dotted reference line represents the required orientation for the code "AGDA6A4".

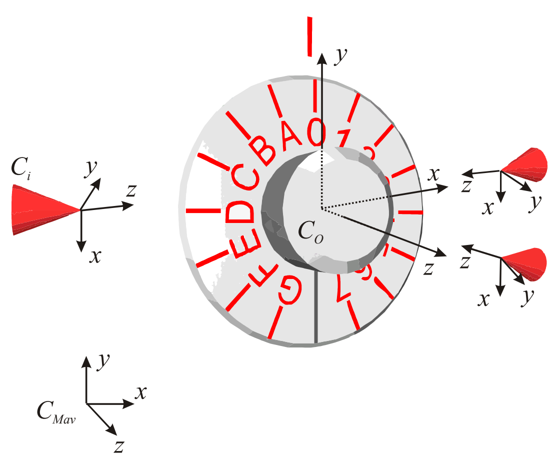

Figure 6.14: Coordinate systems of the fingertips and the safe knob.

Forces and torques exerted on the knob with regard to the object coordinate system C_0 (Figure 6.14) are shown in Figure 6.15. The force in *x*-direction is applied to keep the object grasped while the force in *y*-direction results in rotation of the knob. The highest torque is exerted around the rotational *z*-axis of the knob while the torques around the other two axes are much lower. The dashed reference line in Figure 6.15 shows the torque which corresponds to the specific safe combination (e.g. symbol "A" corresponds to the torque of about 0.25 Nm, "B" to 0.50 Nm etc.).

In Figure 6.16 the fingertip forces as assessed in the thumb, index and middle finger are presented. The force components for each finger correspond to the coordinate systems shown in Figure 6.14. The results of the knob rotation in the clock-wise direction (i.e. negative torque T_z) show that the lateral forces of the thumb and the index finger were used to control the movement while the lateral force applied by the middle finger was much lower. Middle finger, however, applied much greater normal force in the opposition with the thumb. When rotating the knob in the counter clock-wise direction, the thumb and the middle finger were correlated more. The results show that during the rotation, the subject also increased the normal force of the fingertips (F_z). The force component in *y*-direction was kept at a low level at all times.

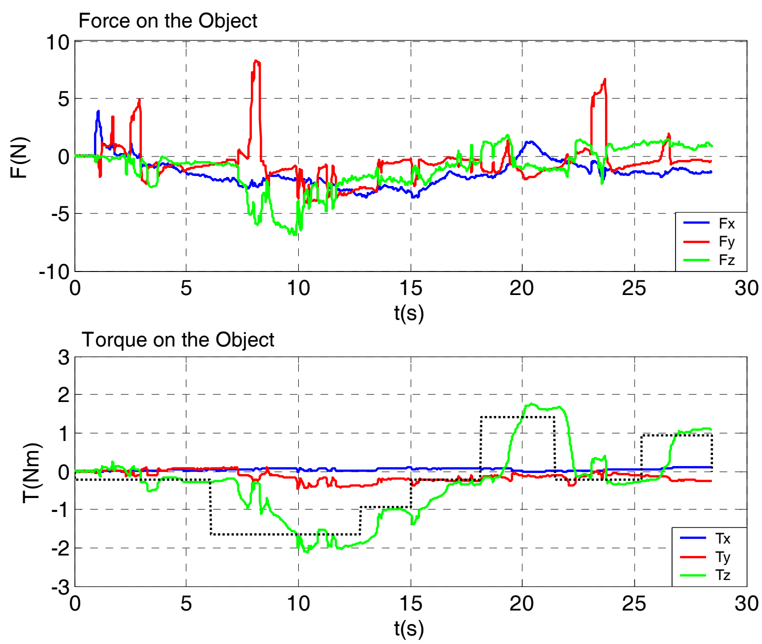

Figure 6.15: Forces and torques exerted during the rotation of the knob.

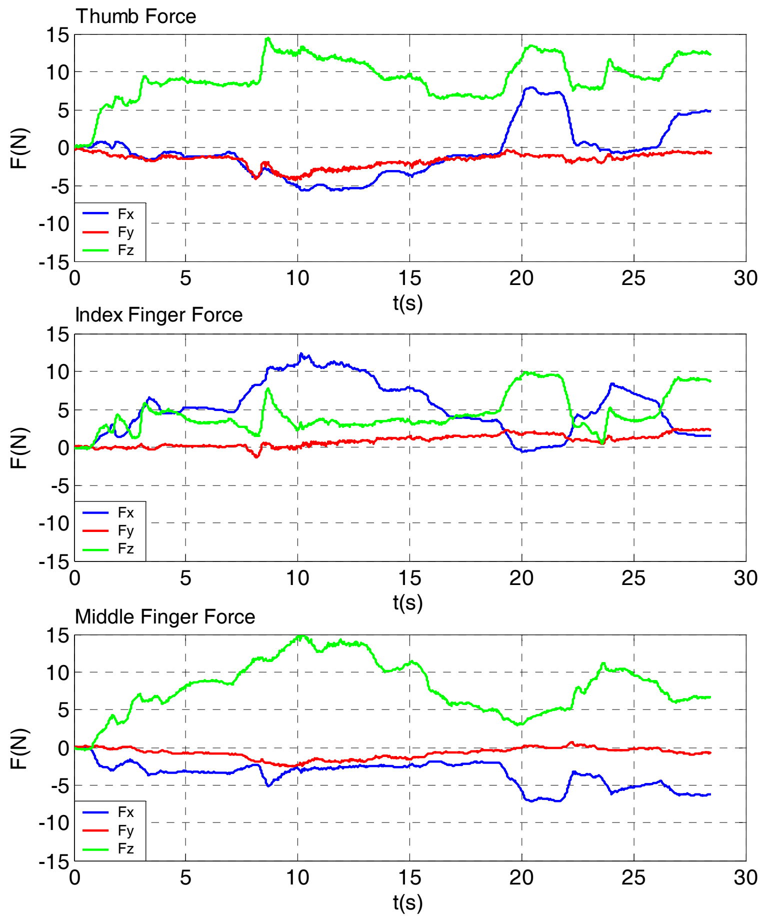

Figure 6.16: Fingertip forces applied during the safe opening.

Figure 6.17 shows the time needed to open the safe in five healthy subjects as obtained in four sessions. Each session consisted of three trials. The subjects performed the task on the middle level of difficulty with the safe combination length of 7 characters and the maximal required torque of 1.9 Nm. The results show that in the first few trials the subjects needed more time to complete the task. The average time of the first session (i.e. first three trials) was 37.2 s (SD 12.1 s) and the average time of the last session (i.e. last three trials) was 25.2 s (SD 4.5 s). The results suggest that the subjects were able to quickly accustom to this VR task. After the first three trials the performance scores remained steady in the range of the scores obtained in the last session. The variability of the results was much lower at the end of the assessment as compared to the first few trials.

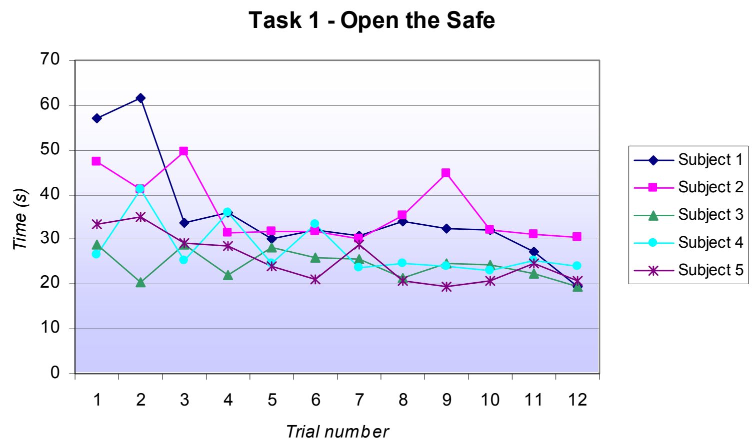

Figure 6.17: Time needed to complete the task as compared among five healthy subjects.

6.7.2 Fill the Jar

In this task subjects had to fill up a jar with water. Figure 6.18 shows the trajectory of the glass COM as recorded during the performance of the task. The subject first grasped a full glass of water and poured the water into the jar by slowly tilting the glass. Next, the glass was brought under the water tap, filled up and poured into the jar. The same sequence was repeated three times. The results show a smooth trajectory during the transport phase. The subject tried to keep the glass steady when filling it with water. Figure 6.19 shows the height of water inside the glass and the jar during the task performance. The results of the water height can be used to identify transport, filling and emptying phase when assessing performance of each segment of the task.

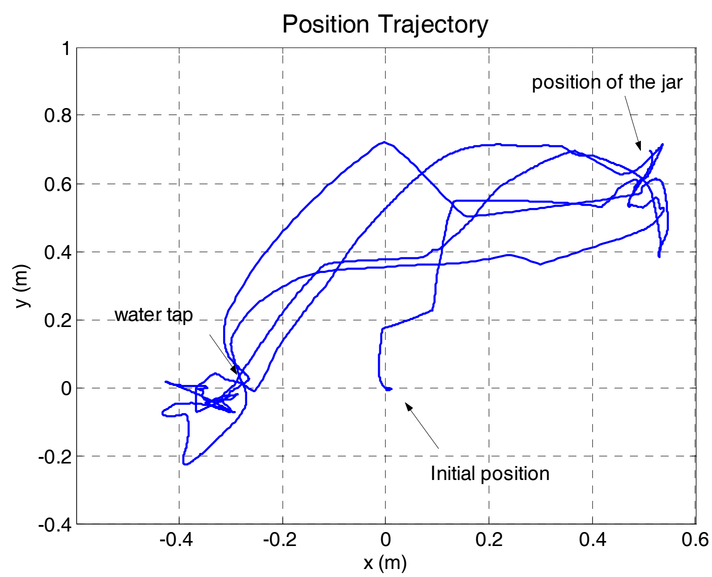

Figure 6.18: Position trajectory of the glass.

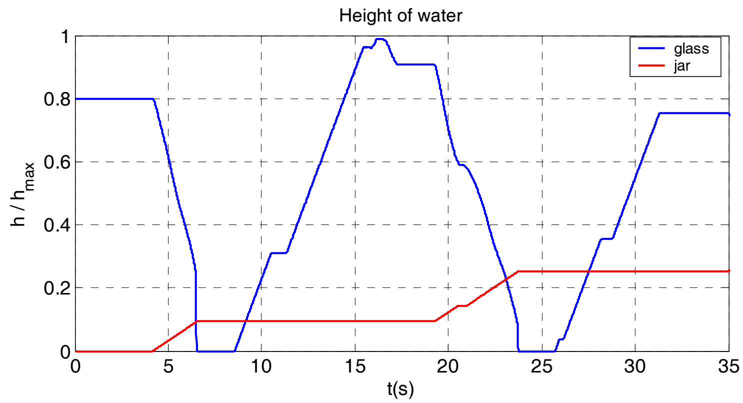

Figure 6.19: Height of water inside the glass and the jar.

Figure 6.20 shows the position (above) and rotation (below) of the glass during the task performance. The output trajectories are smooth in both directions. When the water was poured out, the rotation angle of the glass slowly increased to about 90˚ (π/2 rad). During the transport phase, the glass was kept stable with only small deviations from the horizontal position.

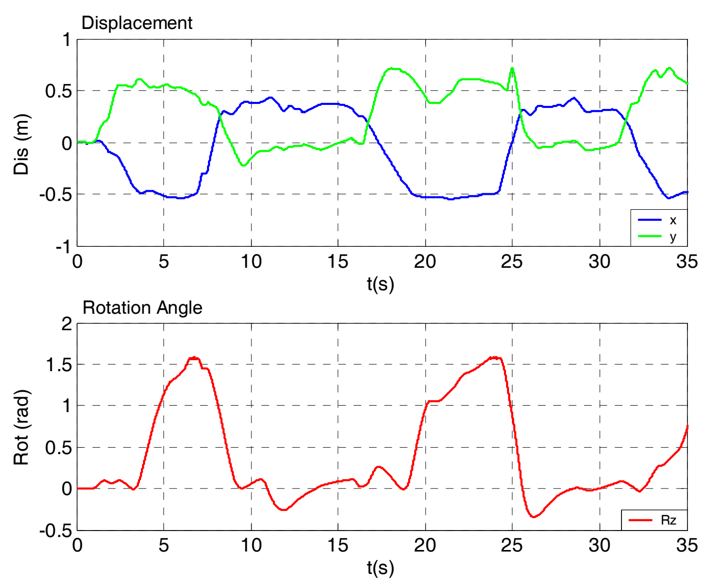

Figure 6.20: Position and orientation of the glass during task performance.

Figure 6.22 shows the forces and torques exerted on the glass. The grasping force used was much lower as compared to the previous task. The force in the *x*-direction and the torque around the *y*-axis (see Figure 6.21) slightly increased when the glass was tilted to pour out the water. The results show that only small torque was exerted around the horizontal axis and almost no torque was applied around the *x*-axis. The motion of the glass was restricted to the *x*-*y* plane of the global coordinate system C_{Mav}. The results show that virtually no force was applied in the restricted degrees of freedom suggesting that the subject was able to quickly accustom to the requirements of the task and movement constraints.

Fingertip forces as assessed during the performance of the task are shown in Figure 6.23. The results show an increase of the normal force in all fingers when the glass is lifted. The grip force decreased when the glass was empty (time interval 24-26 s). The lateral force in the *x*-direction increased during the transport phase and the emptying phase. The middle finger was employed more than the index finger to coordinate the movement of the object. The lateral force applied by the index finger appears to have lower correlation with the thumb force trajectory. The force components in the *y*-direction of all three fingers were kept below 5 N.

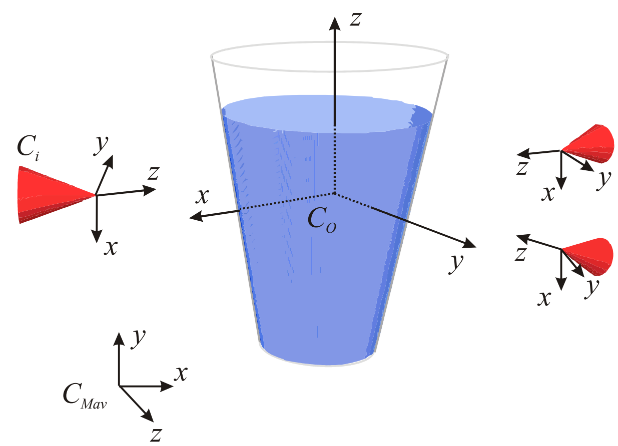

Figure 6.21: Coordinate systems of the fingertips and the glass.

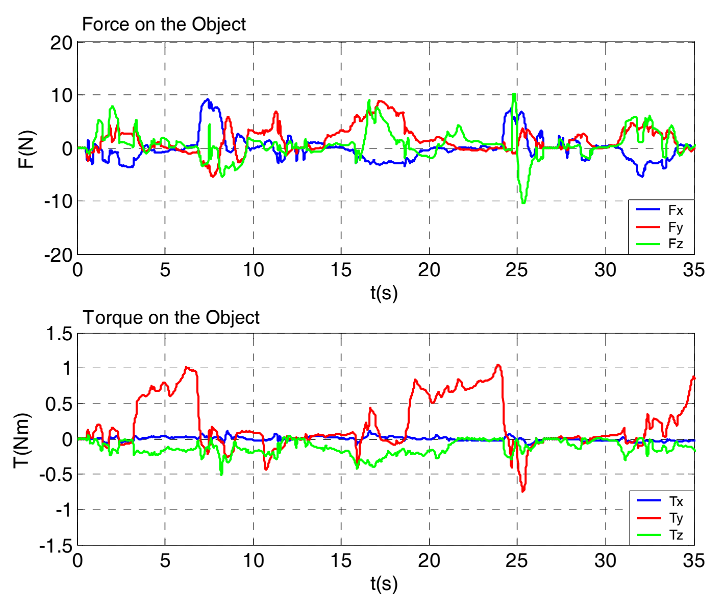

Figure 6.22: Forces and torques exerted on the glass during the task performance.

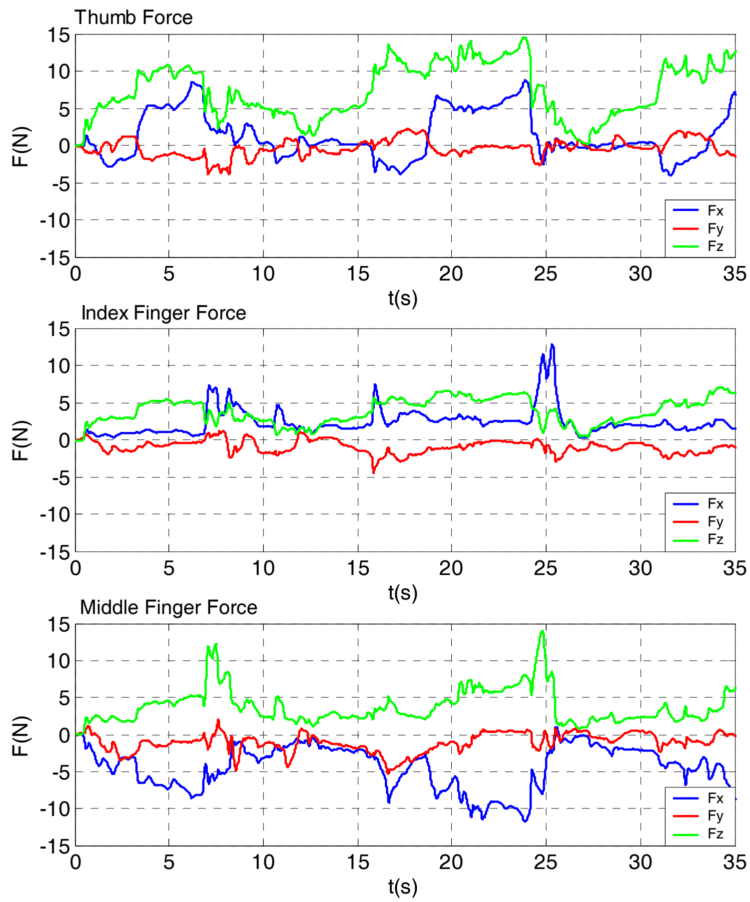

Figure 6.23: Fingertip forces applied on the glass during the task performance.

Figure 6.24 shows the performance scores of the second task as assessed in five healthy subjects. The task required the subjects to fill up the jar to 30% of its volume while the parameters of the task were set on the easiest level of difficulty. The average time needed to fill up the jar was 63.2 s (SD 18.9 s) in the first session and 39.0 s (SD 8.3 s) in the last session. Comparing the performance of this task with the first task shows that the subjects needed more training, about 5 to 6 trials in total, to show consistent performance. The complexity of this task is much higher because the task requires control of three degrees of freedom (*x*-*y* position of the glass and orientation). The results show that the subjects considerably improved their performance during the four training sessions. Variability of the scores among the subjects was much lower in the last few trials as compared to the beginning of the session.

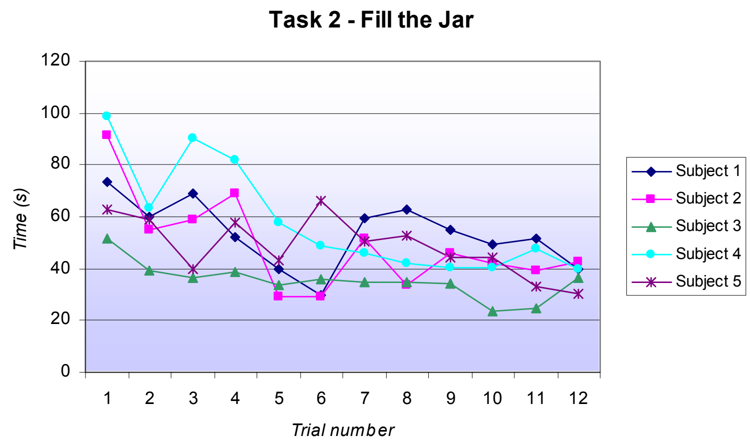

Figure 6.24: Time needed to complete the task as assessed in five healthy subjects.

6.7.3 Elastic Torus

In this task the subject had to grasp and release an elastic torus according to the color of the torus. The task is aimed to increase grip strength and improve grip force control with repetitive "opening" and "closing" of the hand. Figure 6.25 shows the compression force applied to the elastic torus as measured during the first 20 s of performance. The dotted line represents the required force level set for this subject. The subject was required to hold the grip force above the level of 40 N for at least 2 seconds before the target would change to a new value. The results show that the subject consistently applied the compression force without large deviations and responded quickly with the time delay of about 300 ms.

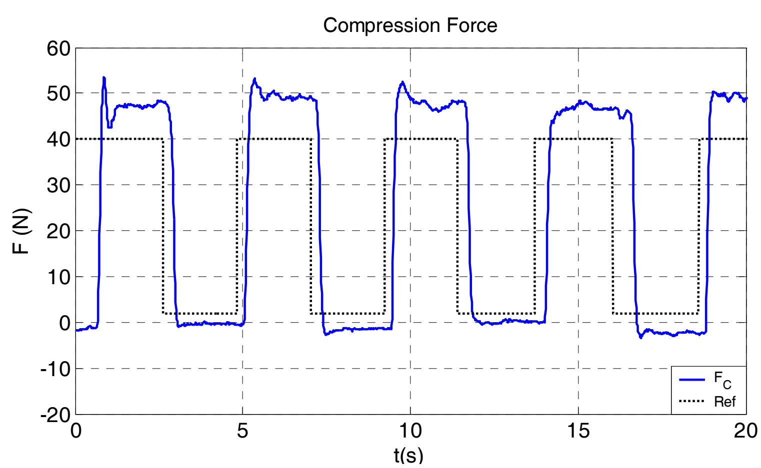

Figure 6.25: Compression force applied on the torus according to the reference force.

Figure 6.27 shows the total force and torque on the object without the internal forces with regard to the coordinate system shown in Figure 6.26. The highest torque was applied around the *z*-axis resulting from the lateral forces of the fingertips exerted during the compression phase. Figure 6.28 shows the corresponding fingertip forces during the performance. The highest force was applied in the normal direction. The normal forces were equally balanced between the index and middle finger when compressing the torus. The lateral force of the index finger was applied in the opposite direction as for the middle finger and resulted in rotation of the torus. The force applied in the *y*-direction was minimal in all fingers.

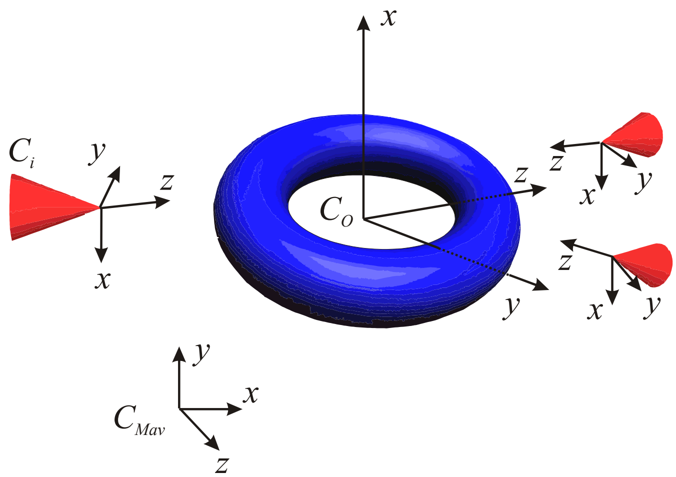

Figure 6.26: Coordinate systems of the fingertips and the elastic torus.

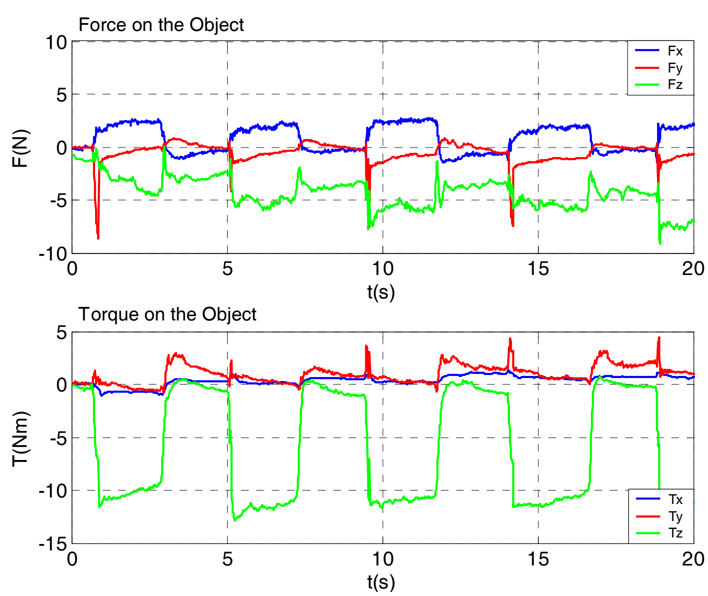

Figure 6.27: Forces and torques exerted on the elastic torus during repetitive "closing" and "opening" of the hand.

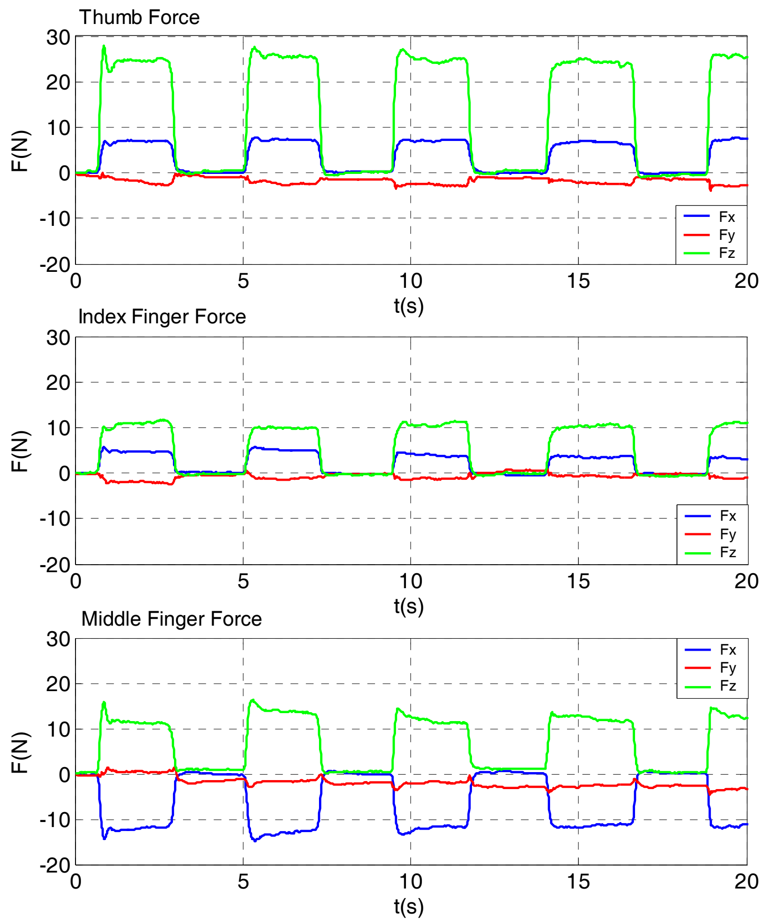

Figure 6.28: Fingertip forces applied on the elastic torus during the task performance.

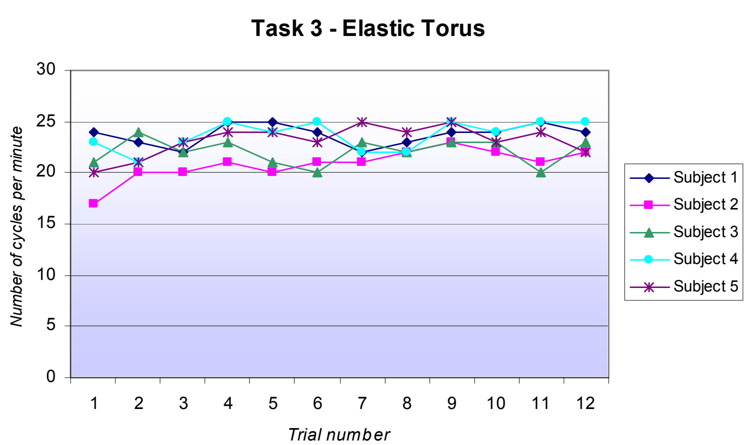

Figure 6.29: Number of task cycles (i.e. hand opening and closing) per minute as compared among five healthy subjects.

Figure 6.29 shows the number of task cycles per minute consisting of repetitive hand opening and closing. The level of difficulty was set on the maximum for this training task with the force range of 40 N and the minimal time delay of 2 s for each phase. The results show steady performance in all 12 trials suggesting that the subjects required very little initial adjustments to successfully perform this task. The average number of cycles per minute was 23.1 (SD 1.5).

6.7.4 Tracking Task

The tracking task is aimed to evaluate the progress of the VR training. Based on our previous research [63], we used a sinus signal with the changing frequency. The use of non-periodic signals reduces fatigue and learning effect. The force output in Figure 6.30 shows only small deviations from the target for this subject. The subject performed the task with high accuracy (rrmse = 0.35).

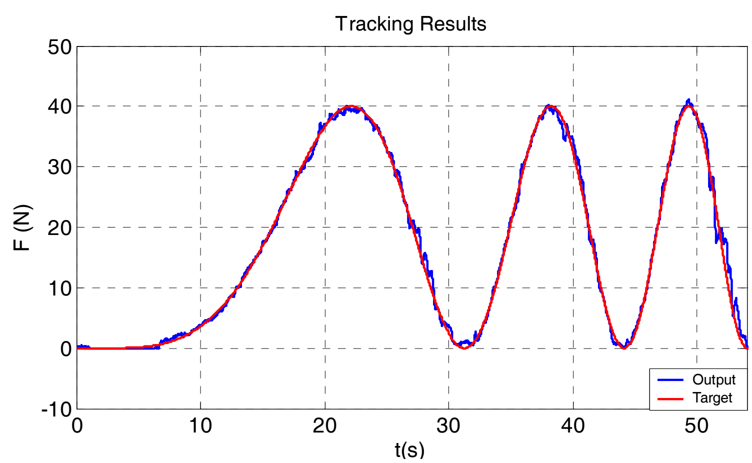

Figure 6.30: Grip force output during the tracking of the modulated sinus signal. The task was performed with only small deviations by the healthy subject.

The corresponding fingertip forces are shown in Figure 6.31. The tracking task required the subject to apply the grip force according to the target. The results show high coordination of force between the index and middle finger. The force produced in the normal direction was equally distributed between the two fingers in opposition with the thumb. The lateral force was mainly produced in the *x*-direction. Although the visual feedback was provided only for the total force applied in the normal direction, the subject produced only small amplitudes for the lateral force. The results of the fingertip forces during the grip force tracking task can provide additional information on force coordination between the fingers. In patients with reduced grip force control, the fingertip forces can be analyzed to adjust the parameters of training according to individual abilities. For example, if the tracking task shows that a patient is unable to control the lateral forces, the compliance of the virtual springs in other VR tasks can be adapted to emphasize more the coordination of the affected force components.

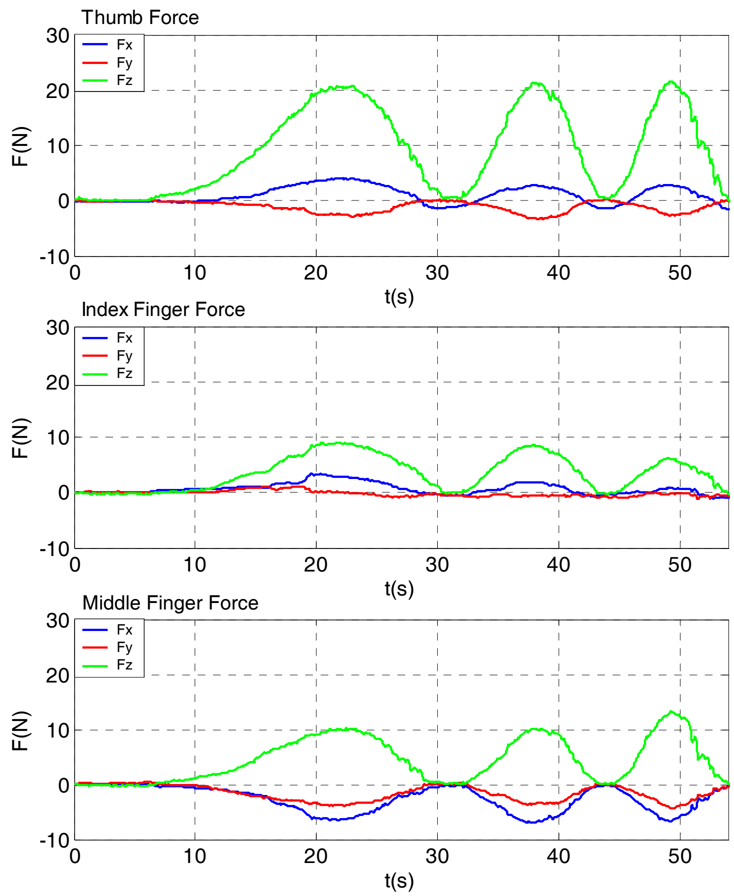

Figure 6.31: Fingertip forces as assessed during the tracking task. The results show high coordination of force between the fingers.

Figure 6.32 shows the tracking error results of 12 trials as assessed in the five healthy subjects. The subjects tracked a sinus signal with the changing frequency and amplitude of 40 N as shown in Figure 6.30. The results show that the tracking error gradually decreased in the first half of the trials and then remained steady in the second half of the tests. The average tracking error in the first session was 0.30 (SD 0.05). The subjects improved their performance and decreased their average tracking error to 0.22 (SD 0.04) in the last session. The difference between the beginning and the end of the experiment was relatively small.

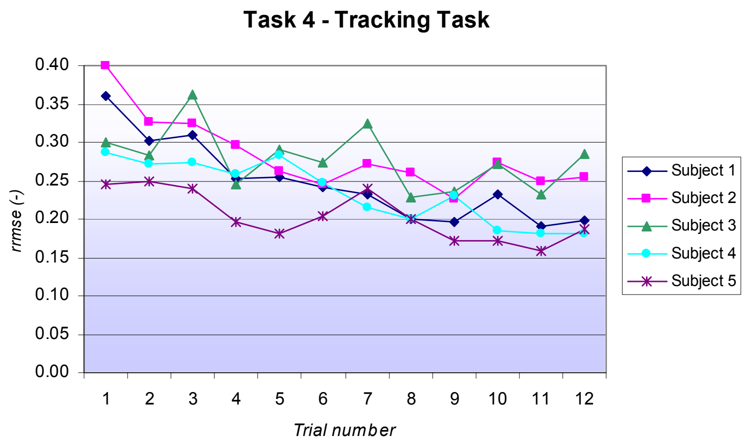

Figure 6.32: Tracking error in the tracking task as compared among five healthy subjects.

6.8 Results in a Patient after Stroke

The performance with the presented VR rehabilitation system was examined in 47-year-old male patient who suffered stroke 7 years ago. The patient had right hemiplegia with reduced ability to control the arm and hand muscles. High level of spasticity was present in finger flexors of the right hand limiting the patient to control the movement of the fingers. The grip strength of the contralateral hand was also significantly reduced.

In the first session the VR training tasks were introduced to the patient who then performed several trials with the less affected hand. The patient was able to perform the tracking task and the elastic torus task already in the first attempt. The safe opening task posed a bigger challenge because it required simultaneous control of the fingertip forces in two degrees of freedom (i.e. grasping and turning). The patient needed more explanation to understand the task. After initial instructions and several attempts, he was able to perform the task on his own. The "Fill the jar" task appeared to be the most difficult task. The patient was initially not able to understand how to move the glass. After several attempts he was able to transport the glass and later on also tilt the glass to pour out the water. In the first trial the patient required 767 s to complete the task on the lowest level of difficulty while in the second session he considerably improved his performance and filled up the jar in only 234 s. The healthy subjects on the other hand required on average 63 s to complete this task in the first session.

After performing all four tasks with the unaffected side, the patient tried to perform the tasks with his right hand. Due to intense spasticity he had difficulty placing the fingers into the finger device. He first performed "Elastic torus" task where repetitive closing and opening of the grip is required. The maximal force was set at only 10 N because of the reduced grip strength in his right hand. When performing the tracking task, he was not able to control the force as accurately as with the left hand. The patient was not able to perform the other two tasks with the affected hand due to a high level of spasticity. Six to eight trials were recorded for each task. In the following sections we present some of the preliminary results as assessed in this stroke patient.

6.8.1 Open the Safe

The patient performed the task on the lowest level of difficulty with the safe combination of five symbols and the maximal required torque of 1.5 Nm. Figure 6.33 shows the fingertip forces as assessed in the thumb, index and middle finger of the less affected hand when opening the safe. The results show that the patient applied much higher normal force (*z*-axis) when rotating the knob as compared to a healthy subject (Figure 6.16). The output force appears to be fluctuating more when lower torque was required. The patient mainly used the thumb and the middle finger to perform the task. The orientation of the knob during the safe opening is presented in Figure 6.34. The output response shows that the patient had more difficulty controlling low-level torques.

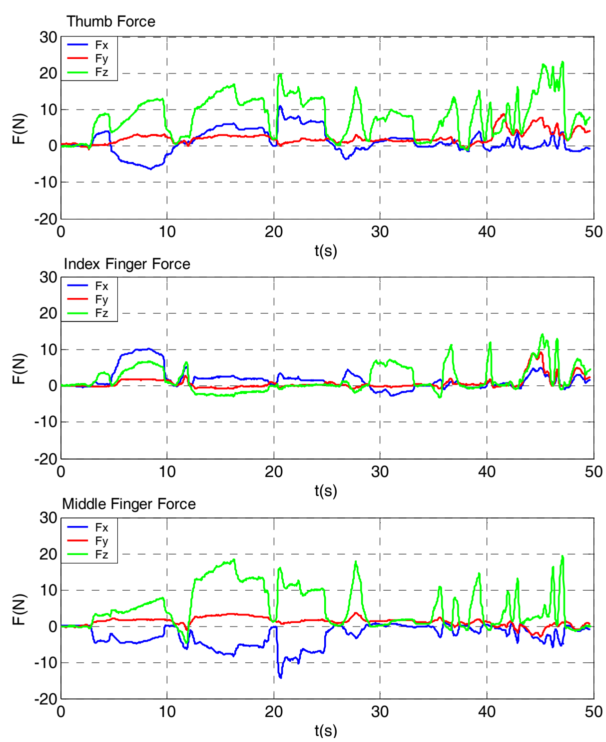

Figure 6.33: Fingertip forces exerted to rotate the knob as assessed in a stroke patient.

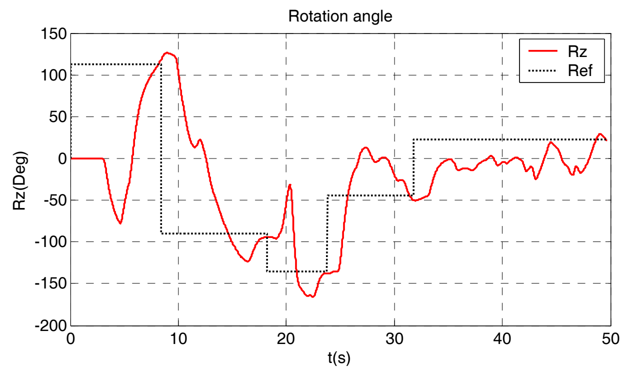

Figure 6.34: Rotation angle of the knob during the safe opening.

Figure 6.35 shows the time needed to complete the first task as obtained in 8 trials. The results in the less affected hand show gradual improvements in performance. The patient was able to open the safe twice as fast in the last session as compared to the first session. Due to spasticity the patient was not able to perform this task with the affected side.

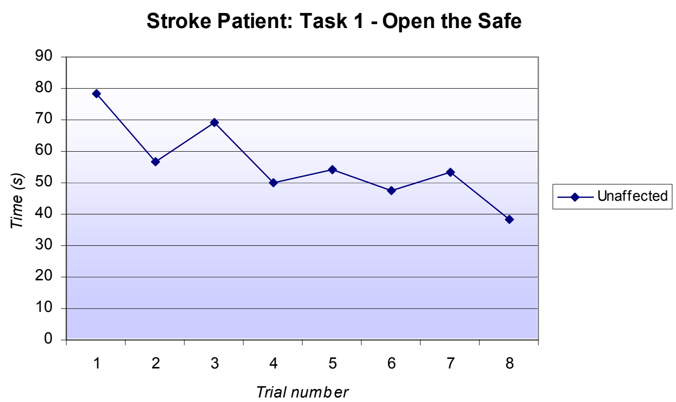

Figure 6.35: Time needed to open the safe as assessed in a patient after stroke.

6.8.2 Fill the Jar

Figure 6.36 shows the position trajectory of the glass from the beginning to the end of the trial. The patient required 234 s to complete the task. The results show irregular movement patterns during performance. The patient had difficulty to simultaneously control the position and orientation of the glass when pouring the water into the jar. In several attempts the patient missed the top of the jar and had to refill the glass.

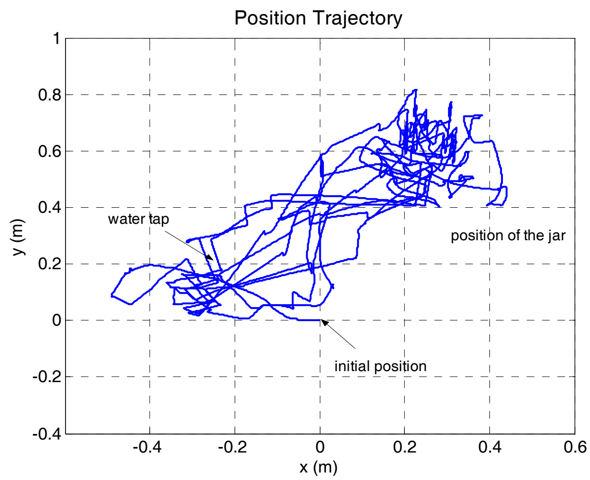

Figure 6.36: Position trajectory of the glass as assessed in a stroke patient when performing the task with the unaffected side.

Figure 6.37 shows a typical sequence of the task (i.e. filling the glass, transporting it over the jar and pouring out water). The patient mainly used the thumb and index finger to perform the task. Due to a reduced control in the fingers, he applied the force in bursts instead of exerting smooth fingertip force. The corresponding position and orientation of the glass are shown in Figure 6.38.

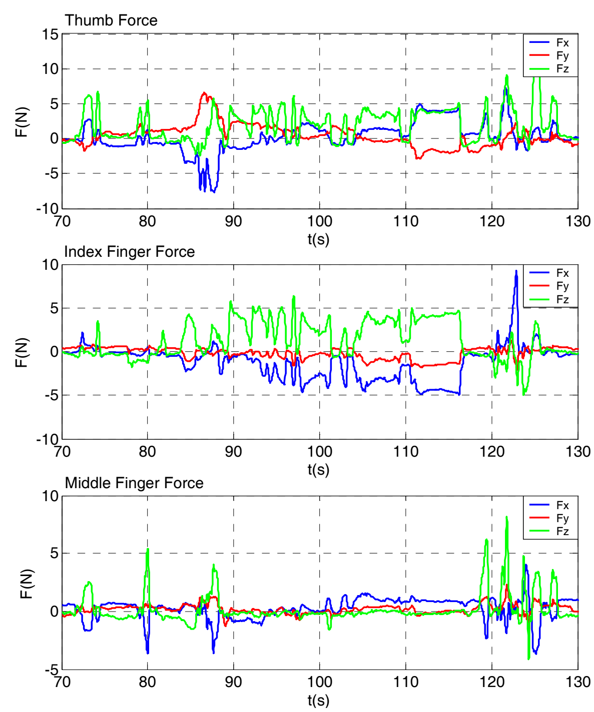

Figure 6.37: Fingertip forces applied on the glass during one sequence of the task (i.e. filling the glass, transporting it and pouring out water) as assessed in a patient after stroke.

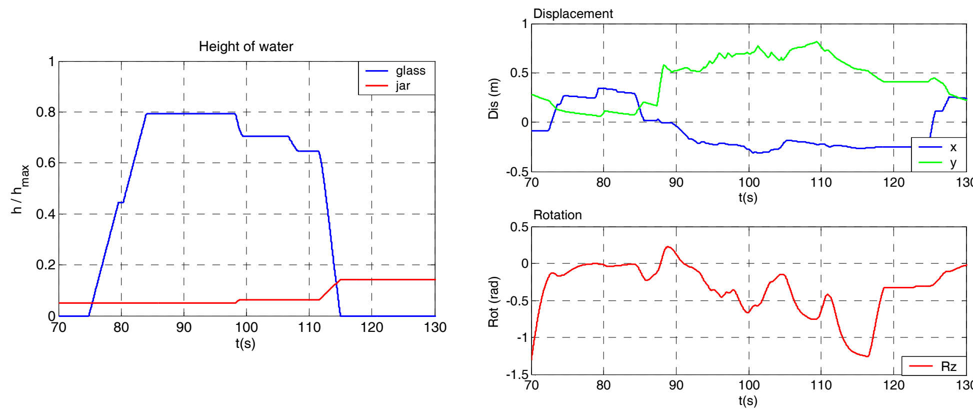

Figure 6.38: Height of water in the jar and the glass (left) and the position and orientation of the glass (right) during a typical performance sequence as assessed in a stroke patient.

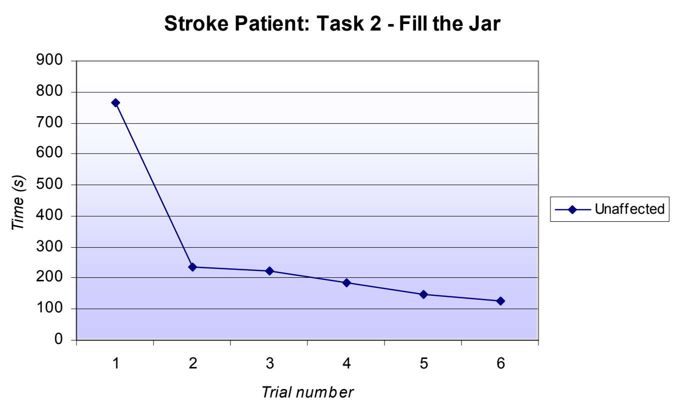

Figure 6.39: Time needed to complete the task as assessed in each trial.

Individual results of each session are presented in Figure 6.39. The patient required 767 s to complete the task in the first trial. The performance was improved considerably in the subsequent trials. The results show gradual decrease of the performance time. The average time needed to complete the task was about three times as large as compared to the healthy persons (Figure 6.24).

6.8.3 Elastic Torus

The patient was able to perform this task with both hands already in the first session. The results of the exerted grip force are presented in Figure 6.40. The maximal required force on the lowest level of difficulty was set at 10 N, shown as dotted rectangular line. The patient was required to hold the grip for one second when reaching the required target level. The results obtained in the less affected hand (Figure 6.40, left) show that the patient responded quickly to the changes of the reference force and performed about 18 cycles (opening and closing of the hand). The performance of the affected hand was considerably lower (Figure 6.40, right). The patient needed more time to open or close the grip due to high level of spasticity which resulted in slower performance with the score of about 10 cycles per minute.

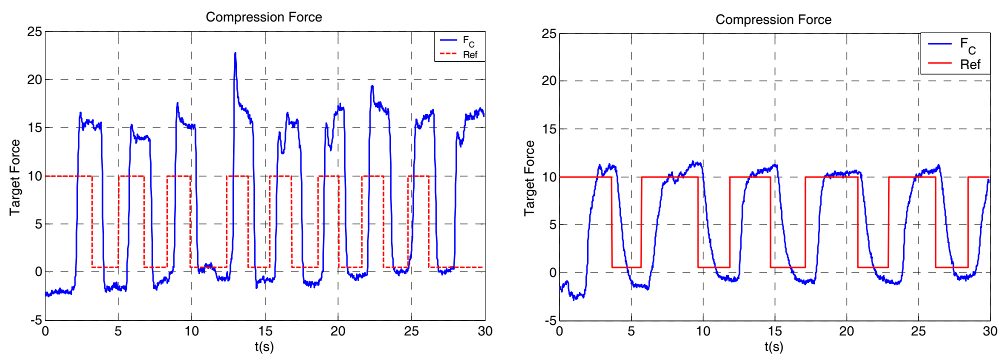

Figure 6.40: Grip force applied on the elastic torus when performing the task with the unaffected (left) and the affected hand (right).

Figure 6.41 shows the corresponding fingertip forces as assessed in the unaffected (left) and the affected (right) side. The results of the unaffected hand show that the patient mainly used the thumb and middle finger to perform the task. He applied large lateral force (F_x) with both fingers when closing the grip. The results obtained in the affected hand show reduced control in the index and middle finger. The patient mainly used the thumb to compress the torus while only minor forces were applied by the two fingers. The results of the middle finger show large lateral forces exerted due to spasticity which affected patient's fingertip force coordination.

Figure 6.42 shows the corresponding correlation plots between the normal thumb force and the normal force exerted by the index and middle finger for the unaffected and affected hand. High (Pearson) correlation coefficient between the thumb and the finger force indicates that the patient is precisely coordinating the exerted force between the opposing fingers, while a low correlation coefficient suggests reduced coordination between the fingers. The results of the unaffected hand show equal distribution of force among the fingers (Figure 6.42, left). The coordination of force is much lower when performing the task with the affected hand (Figure 6.42, right).

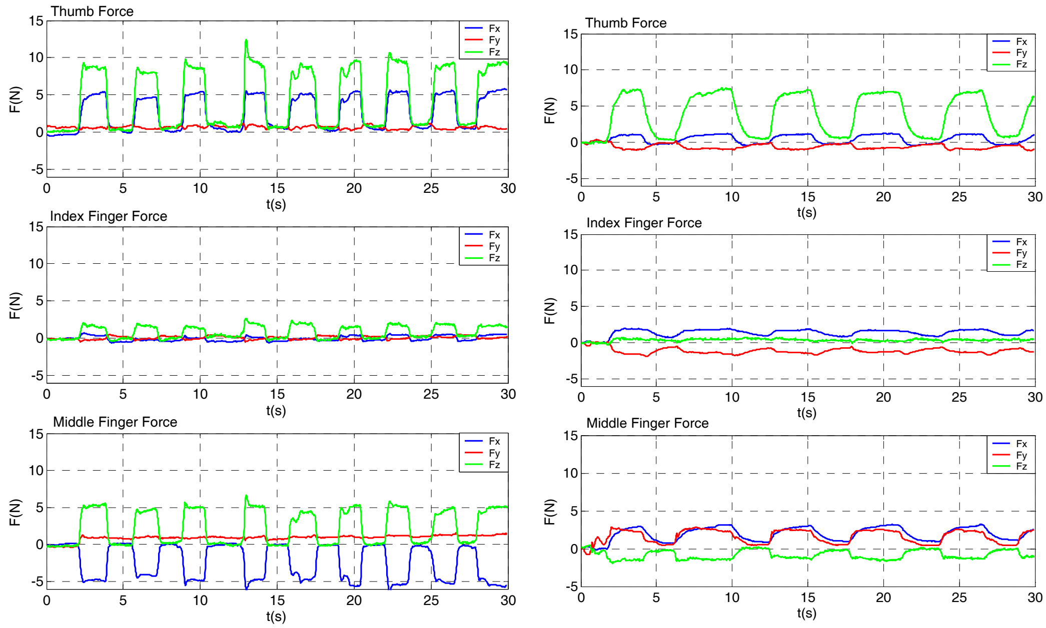

Figure 6.41: Fingertip forces applied on the torus as assessed in the unaffected (left) and the affected side (right).

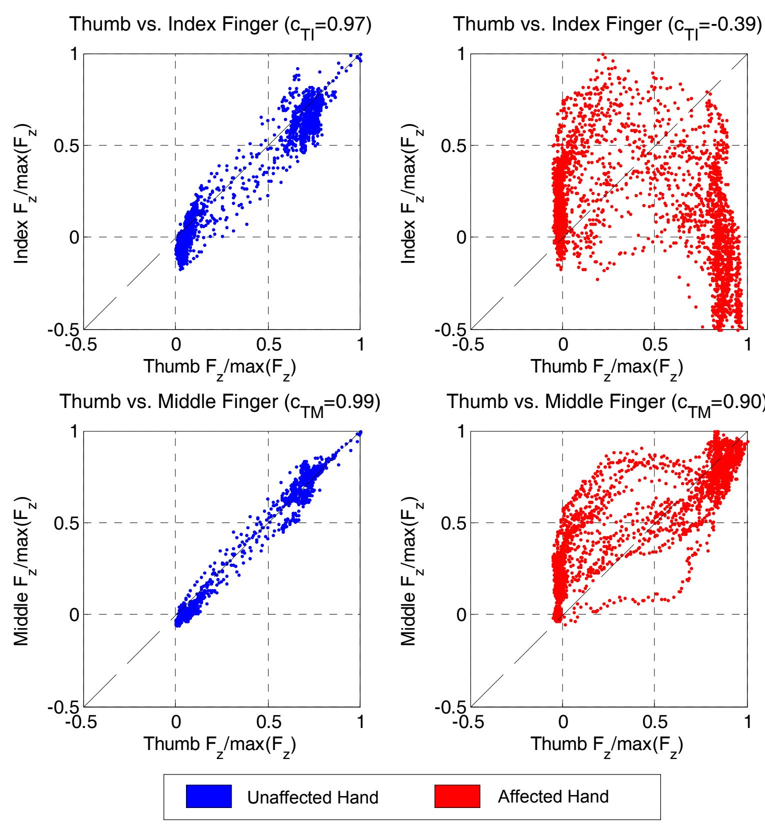

Figure 6.42: Correlation of the normal force between the thumb, index and middle finger of the unaffected (left) and affected hand (right) during the performance of the task.

The performance score of each trial is presented in Figure 6.43. The results show gradual increase in the number of task cycles per minute in both hands. The patient demonstrated much higher performance when using the unaffected hand.

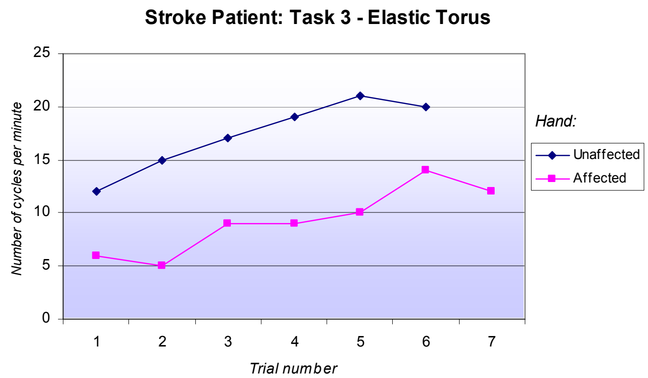

Figure 6.43: Number of cycles per minute as assessed in the unaffected and affected hand.

6.8.4 Tracking Task

The results of tracking the modulated sinusoidal target are presented in Figure 6.44. The patient performed the task with greater accuracy when using the unaffected hand. The results show lesser deviations from the target. When performing the task with the affected hand, the patient had difficulty releasing the grip to track the target at the lower levels of force. The corresponding fingertip force is shown in Figure 6.45. The results show that the patient mainly used the thumb and the middle finger when performing the task with the unaffected hand. When using the affected hand, the contribution of the thumb to the output force was much greater as compared to the two fingers.

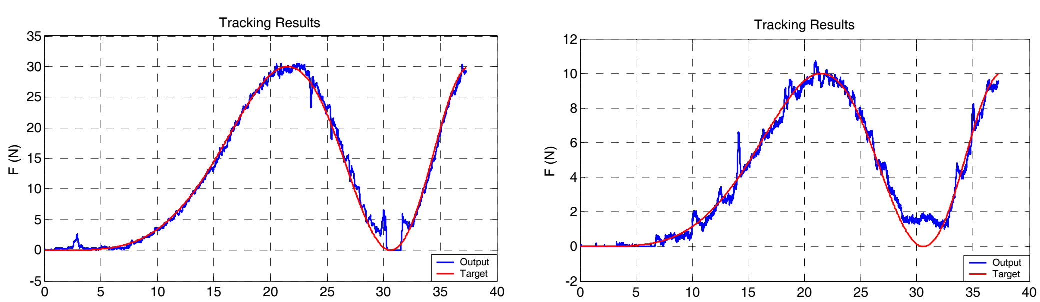

Figure 6.44: Grip force during the tracking of the modulated sinus signal as assessed in the unaffected (left) and affected side (right).

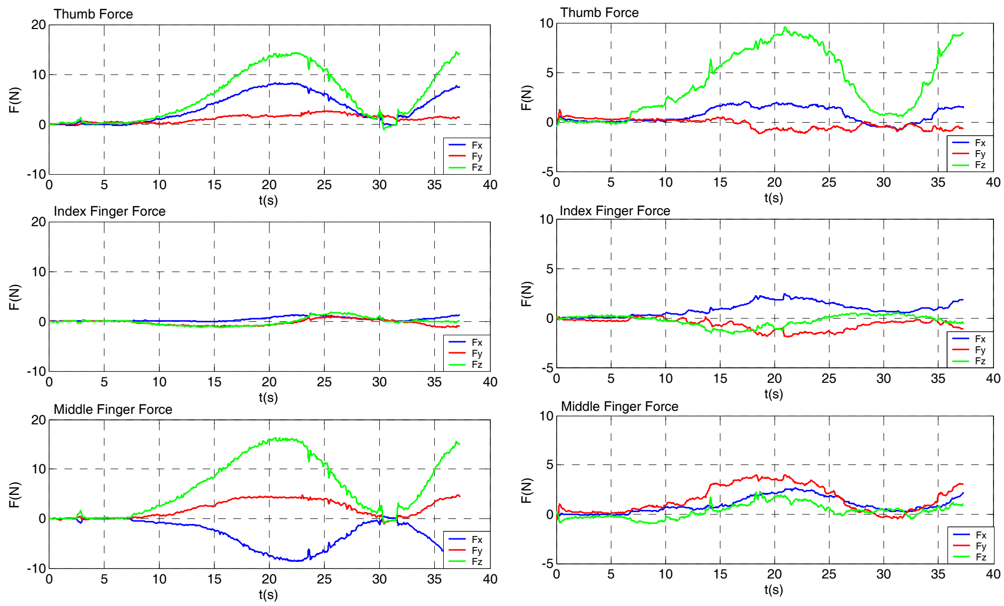

Figure 6.45: Fingertip forces as assessed during the tracking task in the unaffected (left) and the affected side (right).

Figure 6.46 shows the performance of each trial as assessed in both hands. The results show better accuracy of the unaffected hand as compared to the affected hand. The patient showed no considerable improvements throughout the sessions. The results of the unaffected hand are in the range of healthy subjects with the average tracking error of 0.421 (SD 0.172) (healthy subjects: 0.302 (SD 0.046), Figure 6.32). The performance with the affected hand slightly improved only during the first three trials.

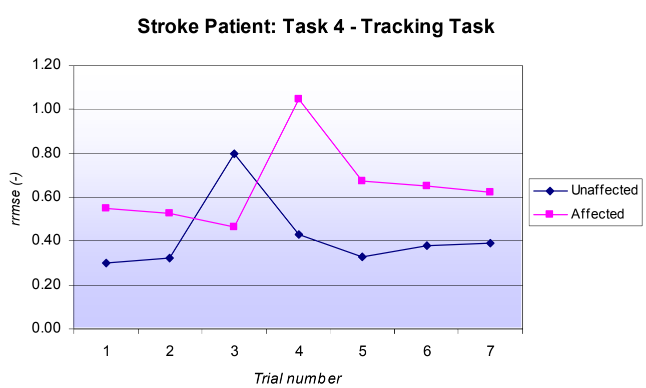

Figure 6.46: Tracking error as compared between the unaffected and the affected side.

6.9 Discussion

In this chapter we have presented a novel virtual reality system for assessment and rehabilitation of hand function. 3By6 Finger Device developed allows accurate measurement of fingertip forces and torques, providing in this way sufficient information to simulate grasping of objects in a virtual world. Although no movement of the fingers is permitted by the isometric device, the visual feedback associated with the object dynamics provides sufficient visual cues to simulate the experience of grasping and manipulation. The programmed VR tasks allow straightforward interaction and provide realistic experience while minimizing the load on the cognitive perception. Only limited number of degrees of freedom (up to three) was used in each task to reduce the complexity of interaction and to avoid depth perception difficulties. The developed VR application allows selection of three difficulty levels, simple user interface with patient database, automated data storage and basic visualization of the results. The system was evaluated in a group of five healthy subjects and one patient after stroke.

The results in the healthy subjects showed that the subjects were able to quickly adapt to the isometric control using the fingertip force. The subjects demonstrated consistent performance in all tasks already after four to six trials. The least adjustments were needed for the elastic torus and the tracking task. We analyzed the correlation of scores between the tasks for each individual. The highest correlation was found between the 1st and 4th task with the average correlation coefficient of 0.64 (SD 0.14). The lowest correlation was found between the 1st and 2nd task with the average correlation coefficient of 0.42 (SD 0.14). Small correlation of results suggests that the subjects who demonstrated superior performance in one of the task were not necessarily as skillful in the other tasks. The measured fingertip forces in all tasks show that only small amount of force was applied along the fingers suggesting that the complexity of the finger device could be further reduced.

The preliminary testing of the VR system in a patient after stroke showed that the patient was able to perform all the tasks at least with the unaffected side. The performance with the unaffected side was much lower as compared to the healthy subjects. After several trials the patient improved his performance in most of the tasks suggesting that further training could possibly promote his sensory-motor abilities. The results of the trials show that he simultaneously used the thumb and only one of the fingers (usually the middle finger) to perform the tasks. The results of the assessment suggest that patient's motor control was reduced in both hands. Due to evident spasticity of the right hand, he was unable to perform the "Open the safe" and "Fill the jar" tasks. The patient had difficulty keeping the thumb of the affected hand inside the finger fixation and was not able to coordinate the lateral force of the thumb. The patient complained about moderate pain in the thumb when using the affected hand and decided not to continue training.

The proposed VR system could be applied not just for training of hand function but also for training of the overall sensory-motor and cognitive functions of stroke patients. The system could be also used in case of an injury or different neural and neuromuscular diseases to train and improve force coordination of the fingers. With the attractive visualization the VR tasks could be especially motivating to children with different sensory-motor disabilities.

The developed 3By6 Finger Device can be also used for the assessment of hand function. In a similar way as shown in Figure 6.42 for the elastic torus, the coordination of force among the fingers could be analyzed for the other tasks. Different characteristics of the measured outputs could be identified to follow the progress of therapy and to identify milestones in the process of rehabilitation. The numerical parameters could include coordination of force between the fingers, correlation of normal and lateral force, regression coefficients between fingertip forces, response time, and frequency analysis.

The isometric finger device could be redesigned to include more cost-efficient force sensors with fewer degrees of freedom. The results have shown that two degrees of freedom per finger would be sufficient for realization of the existing VR training tasks. The input device could be further adapted to specific tasks in rehabilitation therapy. Similar device could be used as an input interface for multi-fingered interaction in virtual environments. The device could consist of a joystick-type handle with force sensors for the fingers. Two or three fingers would be inserted into specially designed finger fixations while the hand would control the position of the handle. The isometric mode would be applied for multi-fingered grasping while the isotonic mode would be used to control the position of the virtual hand.

7 Conclusion

In this dissertation we have presented several novel methods for evaluation and rehabilitation of grasping using computerized assessment in virtual reality. An objective assessment of function is important to evaluate the effectiveness of selected therapeutic approach in order to provide optimal treatment for a patient, maximize therapy outcome and reduce costs. Simple computer assisted tests can provide quantitative and reproducible measurements of physical activity which reflect patient's sensory-motor performance. The main focus of this work has been on the assessment and rehabilitation of grip force control and its coordination during grasping. The assessment of grip force control is important for the evaluation of hand function in patients after CNS injury, patients affected by different neural or neuromuscular diseases and in persons after hand injury.

In this work we have proposed and evaluated three different assessment and rehabilitation systems consisting of a force measurement and visual feedback in virtual environment. The first part of the dissertation presented more complex grip-measuring device with exchangeable end-objects to assess forces in different functional grips. The device was used in connection with the grip force tracking task. The results of the assessment in healthy subjects showed considerable differences in the grip force control among three age groups (e.g. children, young and older adults). The results showed no significant differences in performance between the dominant and non-dominant hand. Future study should compare grip force control in several age groups of children to further investigate the changes of the motor control with age and to evaluate the sensitivity of the tracking method for possible use of the system for the assessment in young children with sensory-motor impairments.

The results of our study in patients with neuromuscular diseases showed that in some patients the disease significantly affected their grip force control in addition to the muscular weakness evident in all patients. Compared to the healthy subjects, many patients produced much larger tracking errors in precision grips which require more accurate muscle control. The presented evaluation method could be used to evaluate muscle activation patterns and fatigue when using different functional grips. Compared to conventional methods, measurement of the grip force in a time frame allows easier detection of changes in muscular strength and sensory-motor functions, which is especially important in patients with neuromuscular diseases.

The proposed tracking system was further applied as an assessment method in a patient after head-injury who was treated with botulinum toxin (BTX) for hand spasticity. The tracking results showed that the treatment with BTX and the physical therapy, improved patient's ability to better control the muscles of the affected hand. The patient was able to release and control the grip with much greater accuracy. The sensitivity of the tracking method should be further investigated on a larger number of patients to validate the effects of BTX treatment on the grip force control and to possibly find parallels between the tracking results and the existing clinical tests.

Several studies which were also reviewed in this thesis have shown beneficial effects of repetitive training with visual feedback. We applied the tracking system as a training method in a group of patients after stroke. The results of the training showed that majority of patients improved their grip force control during the course of rehabilitation. The proposed therapy could enhance the process of relearning the sensory-motor functions after CNS injury. Another advantage of the tracking method is in the quantitative measure provided as a result of the training which can be used to evaluate the progress of therapy. The training with the tracking system was very positively accepted by the patients as well as by the therapists. The therapists reported that the patients were looking forward to daily session and they considered the training tasks as a challenge where they could continuously improve their abilities and receive immediate feedback on their performance.

In the last part of the thesis we presented a novel VR rehabilitation system consisting of the isometric finger device and VR software with four virtual environments for training of hand function. The system allows automated collection of results with database support and visualization of therapy progress which can be reviewed by a therapist or presented to a patient. The preliminary results in healthy subjects showed that multi-fingered interaction with the isometric finger device is very straightforward. The subjects demonstrated consistent performance already after the first few trials. In patients after stroke we expect longer adaptation process due to reduced sensory and cognitive perception. The VR training could be applied at a later stage of recovery to possibly increase the outcome of the conventional therapy. Further information could be extracted from the measurement of the fingertip forces during performance of VR tasks to possibly identify milestones in rehabilitation process. The 3By6 Finger Device could be redesigned to include more cost-efficient sensors with fewer degrees of freedom. In the future a larger scale clinical study should be performed to evaluate the effectiveness of the proposed VR rehabilitation system as the supplemental therapy for stroke patients and persons after central nervous system injury. The patients should be evaluated by the means of standardized clinical measures to follow the progress of VR therapy. The presented VR application could be upgraded to be also used for telerehabilitation where a patient would train with the system at home while connected to a network and linked with the rehabilitation institution. The redesigned finger device could also be attached to a haptic robot arm [69] to simultaneously train arm and hand function in a virtual environment that would emphasize reach-to-grasp movements.

The main advantage of VR for rehabilitation of hand function is in the possibility to apply the training in the earliest phase of recovery after stroke or other condition affecting the sensory-motor functions. In conventional therapy a therapist has to wait for a patient to regain functional abilities in the shoulder and the arm before proceeding with the training of the hand and fingers. With such an approach the patient cannot, for instance, exercise grasping of a glass before having full functionality of the upper limb. The CNS regions involved in the motor control of the hand are in this way neglected until sufficient recovery of other body functions is present. Using a VR system, the patient can begin with the training at a much earlier stage. Even though a patient may not be able to lift the arm and move the glass, he or she can do that same task in a virtual environment where the functional requirements are much lower. Such training initiates the same sensory and motor centers inside CNS which generate the control signals for the muscles involved in the task. The patient can use the existing motor skills to perform the task in a virtual environment and relearn the functional control patterns that would be used in the same task if it was performed in the real world. With the isometric input, the patient needs very low functional force to accomplish a task. As long as some motor activity is present at the fingertips and patient's cognitive and sensory functions are not overly affected, the VR training can be initiated. During the course of recovery a combination of VR rehabilitation and conventional physical or occupational therapy could speed up the recovery process.

Rehabilitation by means of VR technology is becoming increasingly important in rehabilitation research. Although the number of clinical studies is limited and usually involves only a small number of patients, the results are very promising. Rehabilitation in VR has many benefits such as increased patient motivation, flexibility of the training environments, better safety of patients, possibility of telerehabilitation, real-time quantitative information on performance, immediate feedback to the patient, automated data storage and reduced costs. The costs of a new equipment and simplicity in its use are the most important factors contributing to the acceptance of a new therapeutic system in a clinical environment. The VR technology is nowadays becoming more accessible and can be used on most home computers. The interface and measurement devices intended for rehabilitation should be designed with a patient and physical therapist in mind to allow simple use of software and hardware. Several issues still remain, such as transfer of VR training into daily life, benefits of VR-based training as compared to conventional therapy, and computer education of physical or occupational therapists to use VR technology in daily practice.

List of Symbols and Abbreviations

Symbols:	
rrmse	Relative root mean square error
F_0	Output force
F_T	Target force
T	Time period
SD	Standard deviation
K_C	Coefficient of coordination
$\mathrm{F}_{a,b}$	F-test value (ANOVA)
p	Observed significance level
C_i	Contact coordinate system
O_i	Object coordinate system
C_{Mav}	Global (screen) coordinate system
$\boldsymbol{R_{oci}}$	Orientation matrix of *i*-th contact
$\boldsymbol{p_{oci}}$	Position vector of *i*-th contact
$\boldsymbol{P_{oci}}$	Antisymmetrical matrix of vector $\boldsymbol{p_{oci}}$
$\boldsymbol{f_{Ci}}$	Vector of fingertip forces
$\boldsymbol{B_{Ci}}$	Wrench basis of *i*-th contact
$\boldsymbol{F_{Ci}}$	Contact wrench
$\boldsymbol{G_i}$	Contact map of *i*-th contact
$\boldsymbol{G}$	Grasp map
$\boldsymbol{f_C}$	Matrix of fingertip forces
$\boldsymbol{F_0}$	Resulting wrench on the object
$\boldsymbol{x}$	Pose of the object (position and roll-pitch-yaw)
$\dot{\boldsymbol{x}}$	Twist vector of the object COM
$\ddot{\boldsymbol{x}}$	Acceleration vector of the object COM

$\boldsymbol{h}_{\_}$	Friction coefficient in selected DOF
$\boldsymbol{h}_{R\_}$	Rotational friction coefficient in selected DOF
$\boldsymbol{k}_{\_}$	Translational stiffness of virtual spring
$\boldsymbol{k}_{R\_}$	Rotational stiffness of virtual spring
$\boldsymbol{M}$	Inertia matrix
$\boldsymbol{C}$	Matrix of friction coefficients
$\boldsymbol{N}$	Matrix of stiffness coefficients
$\boldsymbol{g}$	Gravity vector
F_x, F_y, F_z	Measured forces in x, y and z-direction
T_x, T_y, T_z	Measured torques in x, y and z-direction

ABBREVIATIONS:	
ADL	Activity Of Daily Living
BMD	Becker Muscular Dystrophy
BTX	Botulinum Toxin
CMC	Carpometacarpal
CNS	Central Nervous System
COM	Center Of Mass
COPM	Canadian Occupational Performance Measure
DIP	Distal Interphalangeal
DOF	Degree Of Freedom
FC	Friction Cone
FSHMD	Facioscapulohumeral Muscular Dystrophy
IP	Interphalangeal
LGMD	Limb-Girdle Muscular Dystrophy
MAS	Motor Assessment Scale
MCP	Metacarpophalangeal
MMT	Manual Muscle Test
PIP	Proximal Interphalangeal
SMA2	Spinal Muscular Atrophy Type 2
SMA3	Spinal Muscular Atrophy Type 3
VR	Virtual Reality

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Appendix A: Neuromodulation, 2003

G. Kurillo, T. Bajd, R. Kamnik, "Static analysis of nippers pinch," *Neuromodulation*, vol. 6, pp. 166-175, 2003.

Static Analysis of Nippers Pinch

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▪ **Abstract**

The purpose of the study was to present a method for the assessment of finger joint torques in two-fingered precision grips. The static analysis of various grips is important for the analysis of the mechanics of a human hand and the functional evaluation of grasping. We have built a grip-measuring device assessing the endpoint forces of two-oppositional grips. Through the simultaneous use of an optical measuring system and the grip-measuring device, the finger positions and the grip force acting on the object were obtained. A recursive computational method was used within the proposed static model of the finger to calculate the finger joint torques. In the paper a three-dimensional static model of the grip is presented and the calculated finger joint torques are shown. The repeatability within subject is analyzed for the assessed grip force and finger joint torques. The estimated joint torques corresponds to the amount of load on the finger joints during the isometric muscle contraction in nippers pinch. ▪

Key Words: biomechanics, finger, grip force, precision grip.

INTRODUCTION

The loss of hand functionality from a central nervous system (CNS) injury or a hand injury can greatly influence a person's everyday life (1–3). Different methods of rehabilitation and therapy, including functional electrical stimulation (FES), can help such people regain a certain degree of functionality in their hands (2,3). The analysis of the mechanical properties of the fingers and assessment of forces and torques acting on the finger joints can provide additional information about hand mobility (4,5) and the amount of load on the fingers during daily activities (6–8).

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Grip-force assessment is also an important factor in hand functionality evaluation (1,9,10). In rehabilitation therapy, most measurements are made by various types of dynamometers, which measure only strength and thus provide only partial information on a subject's grip (11). Capturing the grip force vector (grip strength and direction of the force) can give additional knowledge on the grip performance and coordination (2,4,9). Different researchers (6–8) have proposed instrumented objects to assess the force vectors acting on objects that are in shape and size similar to the objects used in daily living. Instrumented objects allow real-time measurements of the force during the observed grip. In this paper we propose a grip-measuring device with a commercial force sensor to measure grip forces in two-fingered grips.

The assessment of the finger joint torques and fingertip forces provides more information on the mechanics of the fingers and describes the amount of load on the finger joints during a grip applied (5). Different researchers (4,5,12,13) have presented models for the assessment of joint torques from the measured or simulated fingertip force. The purpose of our study was to investigate a method for the static analysis of two-fingered grips that employs simultaneous measurement of the fingertip force and finger joint positions, providing thus the necessary information for the calculation of the joint torques.

In this research the static force analysis of a two-fingered precision grip was performed. A grip-measuring device was designed to record the force vector acting on the measuring object in two-oppositional grips (14,15). Assessing the magnitude and direction of the fingertip force vector can provide an insight into the subject's grip force control which is important when applying motion to the object or keeping the object in a secure grip (9). In case of a neurologic condition or trauma, such information may be useful to determine deviations of one's grasp compared to a healthy subject. The ability to produce strong and well-coordinated two-fingered grip can be reduced due to a brain or spinal cord injury, damage to the ulnar or median nerves, or arthritis (9). The grip force analysis can provide additional information that can be used in hand diagnosis and treatment, for the selection of FES patterns of the upper extremities, and for the functional evaluation of the hand after a reconstructive surgery (2,9,12).

Our study is focused on a nippers pinch that is characterized as a precision grip (14,16). The object is grasped between the finger pads of the thumb and index finger, providing good sensory feedback on the properties of the object. The two fingers in nippers pinch are extended, which allows higher forces to be exerted. The grip is aimed to grasp and manipulate small objects (eg, a pencil, paper clip) where a fine force control and good stability of the object is required. Two-fingered precision grips are used in many activities of daily living (eg, picking up small objects, turning a knob, writing with a pen) and are therefore a significant goal for the restoration of the hand function (4,12), particularly after a hand injury or stroke.

To assess the finger joint torques during a grip, the measurements of the fingertip force and the posture of the fingers are needed. The finger positions were obtained by the optical measuring system. The hand and the finger joints were marked with markers to capture their relative position to the object. It has been demonstrated that optical measurements can be used successfully for the assessment of finger joint positions (17–19). The validity of the method has been addressed by Rash and colleagues (17) who compared the optical 3-D motion analysis with a 2-D video fluoroscopic recording of a finger motion. They reported that the accuracy of such a method of marker placement for the measurement of joint angles is comparable to the errors found in clinical goniometry (± 5°).

In our experiment the grip force was measured by the grip-measuring device developed. From the obtained results, the finger joint torques were calculated recursively (20) by the use of the proposed static model of the human finger. Some results of the measured grip force and joint torques are presented in the paper to provide an insight into the proposed assessment method.

METHODS

Model

In our investigation each finger was modeled as a serial manipulator attached to the palm. The three phalanxes of the finger were modeled as rigid segments connected with different types of joints (2). We used four degrees of freedom (DOF) to describe the movement of each finger (Fig. 1). The proposed complexity of the model is sufficient for the analysis of a simple finger movement (4). Universal joint (2 DOF) models the flexion-extension and adduction-abduction of the proximal joint. Two rotational joints (1 DOF) are used to model the flexion-extension of the middle and distal joints. The approximate mass of the segments for an average male human hand was considered in the calculations. The data were obtained from the Institute of Anatomy, Medical Faculty, University of Ljubljana. The center of mass for each segment was determined by an approximation of the phalanx with a cone-shaped homogenous rigid body (13), where the diameters of the knuckles were measured before the experiment.

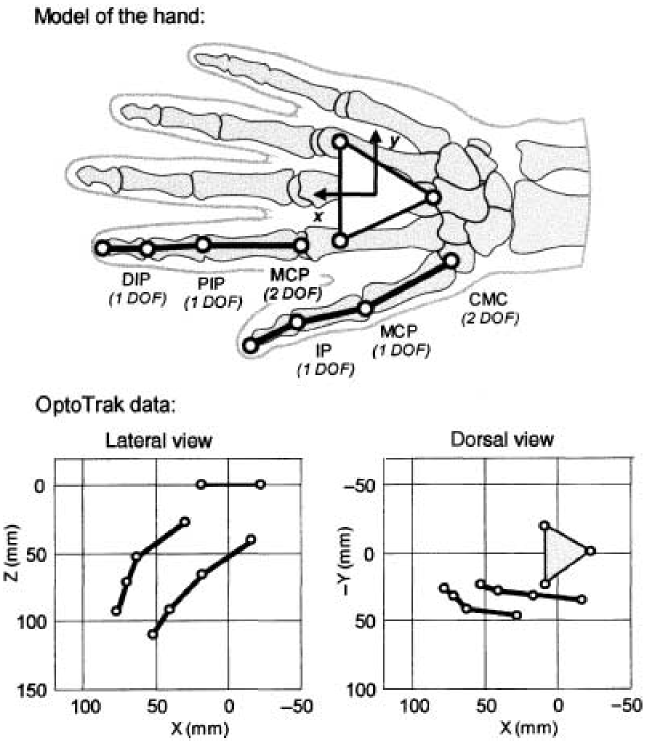

Figure 1. Each finger of the proposed model of the hand has four degrees of freedom (above). A three-dimensional model of the precision grip was assessed with the OptoTrak system (below).

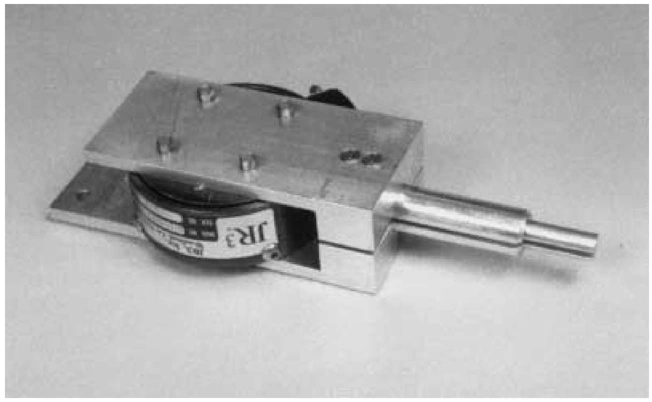

Figure 2. Grip-measuring device was designed to measure the endpoint forces of two-oppositional grips. The instrument is based on the robotic force-wrist sensor and designed to suit a human grip. The two metal parts, which shape into a circular stick to fit human fingers, allow the transmission of fingertip force to the sensory unit.

Method Overview

To calculate the finger joint torques, the measurements of the fingertip force and position of the fingers, relatively to the object, were needed (20). Hand posture was assessed by the optical measuring system OptoTrak (Northern Digital, Inc., Waterloo, Canada) which can accurately (with the accuracy of 0.1 mm) measure the three-dimensional position of infrared markers placed in front of the system of three cameras. Forces acting on the object were measured simultaneously through a specially designed grip-measuring device (Fig. 2).

The OptoTrak system consists of three cameras with fixed relative position and orientation. The active infrared markers are placed in front of the optical system and have to be visible during the measurement. The exact three-dimensional coordinates of each marker are calculated by the system from the known geometry and expressed in the world coordinate system (20), which is the coordinate system defined by the calibration procedure. The system must be calibrated before each measurement session by the calibration plate placed in front of the cameras. Two sets of OptoTrak cameras situated in the opposing direction were used in our experiment. For convenience, all data measured were transformed into a local coordinate system of the sensor (SCS), defined by the three markers applied on the top surface of the grip-measuring device. The defined coordinate system matched with the internal coordinate system of the force sensor. We also defined a hand coordinate system (HCS) on the dorsal side of the hand to follow the relative position of the hand to the grip-measuring device. Two markers were applied at the distal ends of the second and fourth metacarpal and the third marker was attached at the proximal end of the third metacarpal bone (Fig. 1). All three markers formed a triangle on a dorsal plane that was used to position the coordinate system of the hand. The x-axis was oriented along the third metacarpal bone, the z-axis was defined by the normal of the dorsal triangle and oriented into the palm of the hand and the y-axis was parallel to the flexion-extension axis of the metacarpo-phalangeal joint (17).

The rest of markers were attached to the lateral side of the thumb and index finger to mark the position of the joint axes and fingertip. The center of rotation for each joint was determined from the visible anatomic landmarks (15,17). The proximal interphalangeal (PIP) and distal interphalangeal (DIP) joint locations were determined from the

PIP and DIP joint lines on the palmar side of each finger and the metacarpo-phalangeal (MCP) joint location was approximated from the location of the palmar crease at the end of the second metacarpal (17). The markers were placed laterally into the approximated centers of rotation. The placement of the markers was inspected visually and by the optical system where the subject's finger movement was recorded to see whether the relative distance between each two subsequent joints changed. The corrections of the marker positions were made accordingly.

From the measured marker locations, the centers of joints were determined (Fig. 1) and local coordinate systems were placed into the hand segments using the notation adopted from the analysis of mechanical manipulators (20). The joint coordinate system of the segment *i* (JCSi) was placed at the distal end of the corresponding segment as shown in Figure 4. The origin of the coordinate system was translated in the direction perpendicular to the sagittal plane to the center of the knuckle. The *z*-axis of the finger coordinate system corresponded to the normal vector of the sagittal plane defined by the three markers located on the lateral side of the finger. The *x*-axis of each joint coordinate system was defined in the direction of the phalanx obtained from the location of two subsequent markers. The *y*-axis vector was then determined to obtain an orthogonal coordinate system.

A grip-measuring device (Fig. 2) was designed to measure the endpoint forces of two-oppositional grips. The instrument is based on the robotic force-wrist sensor JR3 (JR3, Inc., Woodland, CA) that measures forces in three directions of its coordinate system and a torque around the *z*-axis. The force measurement range of the sensor is 110 N in the *x* and *y* directions (horizontal plane of the sensor) and 220 N in the *z*-axis of the sensor coordinate system. The torque range of the sensor is 10 Nm. The measured force vector corresponds to the amount and direction of the tension between the upper and lower parts of the external surfaces of the sensor body. No displacement is produced due to a high rigidity of the device. The sensor consists of foil strain gauges arranged in wheatstone bridges that are connected to an external amplifier. Each of the four output channels corresponds to one force (torque) component and the cross talk between the channels is compensated. The analog outputs are sampled through an A/D unit and a producer-adjusted calibration matrix is used to transform voltages into the corresponding force (torque) components. The sensor is calibrated with respect to the internal coordinate system that is located in the center of the sensor body. The nonlinearity of the sensor is less than 1% across the range and the resolution of the measurement is 0.01 N.

The grip-measuring device developed consists of two metal parts that are shaped in the form of the letter "L" with two semicircular sticks attached to the front side of the device where the two "L" parts come close together (Fig. 2). The space between the two parts of the measuring object prevents the two halves of the stick to contact each other, even at forces as high as 70 N. The construction allows a simple exchange of differently shaped endpoint objects. When a person grasps the measuring stick, the grip force is translated to the sensor yielding the information on the grip force vector. The metal construction has some compliance in the vertical plane at high-level forces due to the elasticity of the metal and relatively large moment arm (14 cm); therefore the measured force would differ (for about 4% at 35 N) from the applied force at the endpoint of the measuring object. The effect of the compliance on the other two force components in the horizontal plane of the device is not critical because the rigidity of the metal frame is much higher in these two directions. The influence of the moment arm from the point of contact to the sensor coordinate system was compensated through a recalibration procedure. Different weights were placed at the center of the sensor and at the distal end of the device and the measured forces were compared. The calibration matrix was corrected accordingly. The results show (Fig. 3) that the metal frame attached to the sensor does not influence the linearity and accuracy of the measurements after the modification of the calibration matrix. The force characteristic of the measurement at the endpoint object of the grip-measuring device (Fig. 3) is linear with the error of 1.4%. During the experiment we assume that the subject grasps the measuring stick at the distal part of the device.

In the experiment the force vector components measured by the grip-measuring device were

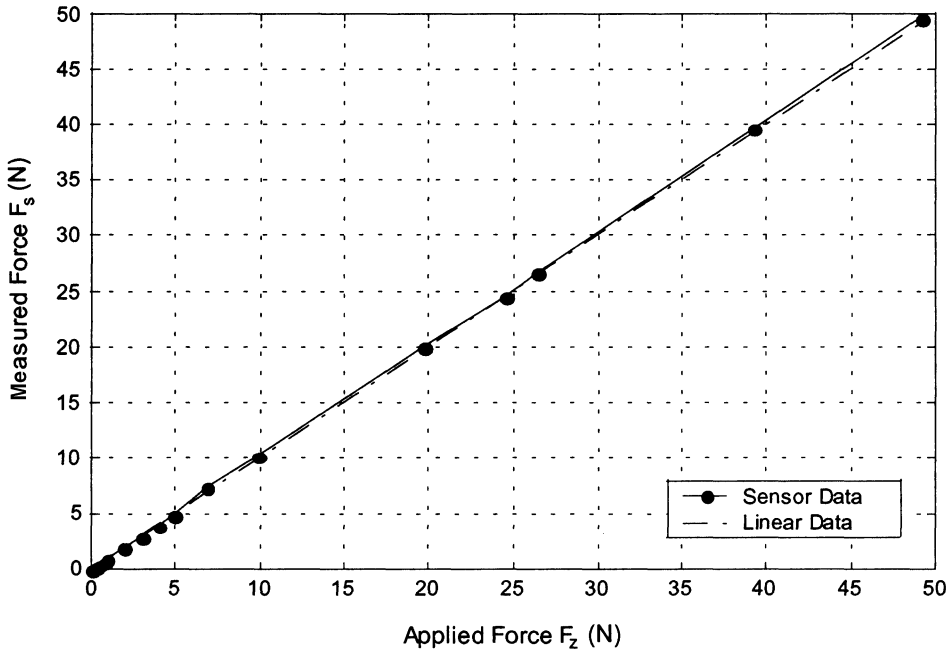

Figure 3. The measured output of the grip-measuring device after re-calibration of the sensor to the application of force F_z at the measuring object shows a linear dependency (error 1.4%). The solid line represents the measured force F_s in the z-axis of the sensor and the dotted line represents the ideal characteristic ($F_s = F_z$).

transformed into analog voltage values and sampled at the frequency of 100 Hz through the A/D unit of the OptoTrak system to obtain the simultaneous data of the grip force and positions of the finger joints. The analysis of the results and the calculation of the joint torques were performed off-line with Matlab software (The MathWorks, Inc., Natick, MA).

Analysis

We used a recursive computational method (20) to calculate the forces and torques acting between the segments of each finger. In the presented calculation the forces and torques are analyzed in the direction from the contact point to the palm of the hand, considering the finger as a serial manipulator (Fig. 4). Each of the two fingers is analyzed separately. The palm was considered as the segment #0, the proximal segment was denoted with the index #1, the middle with #2, and the distal segment with #3. The measured endpoint force and position of the fingertip marker defined the contact with the object. In the calculations we modeled the contact with the object as a point contact with friction (20). The presented model of the hand (Fig. 1) was used in the following calculations where every finger k was analyzed separately ($k = 1$ for the thumb and $k = 2$ for the index finger). All the vectors used in the equations (Eqs. 1–2) are expressed in the coordinate system of the sensor.

First, the equilibrium equations for forces are written for each segment i:

$$^{k}f_{i-1,i} - {}^{k}f_{i,i+1} + {}^{k}m_i g = 0 \qquad \text{(Eq. 1)}$$

The forces that act on the segment i of the finger k (Fig. 4) are: the gravity force $^{k}m_i \cdot g$ (where $^{k}m_i$ is the mass of the segment and g is gravity acceleration), the force $^{k}f_{i-1,i}$ describing the force of the segment $i-1$ acting on the segment i and the negative force $^{k}f_{i,i+1}$ defining the action of the segment $i+1$ on the segment i.

Next, the equilibrium equation for the torques acting on the segment i (Fig. 4) is written with regard to the center of the corresponding finger joint:

$$^{k}T_{i-1,i} - {}^{k}T_{i,i+1} + {}^{k}r_{gi} \times {}^{k}m_i g - {}^{k}r_{fi} \times {}^{k}f_{i-1,i} = 0 \qquad \text{(Eq. 2)}$$

In Equation 2 the vector $^{k}r_{gi}$ connects the joint center with the center of mass for the segment i and $^{k}r_{fi}$ connects the joint center with the end of

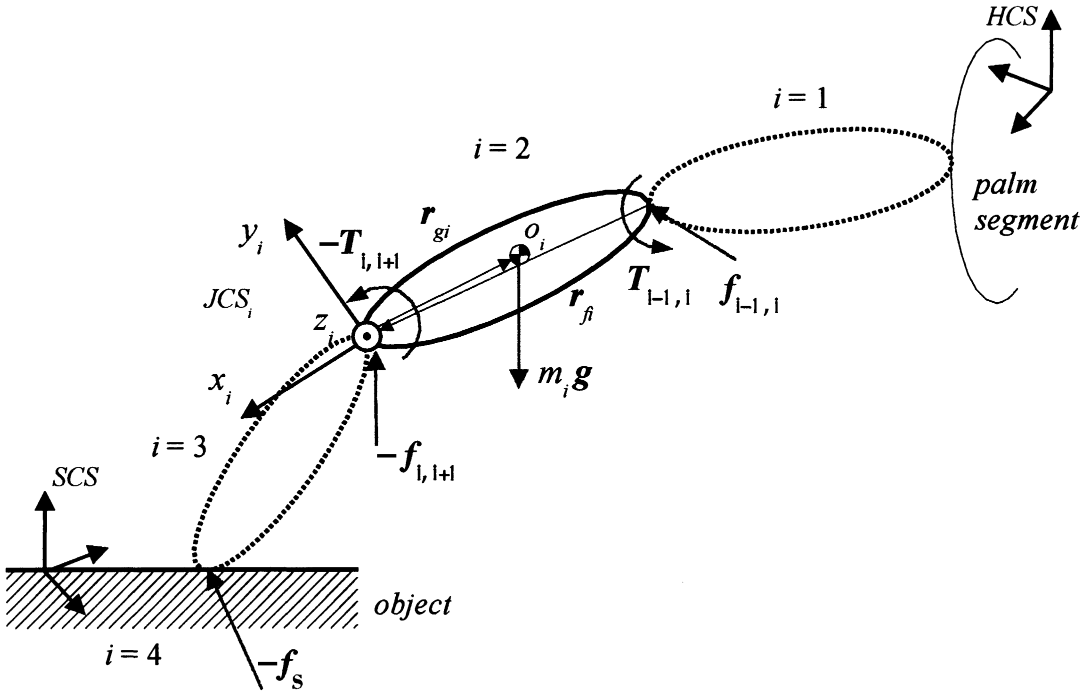

Figure 4. The static analysis of the finger model in the contact with the object. The forces and torques acting on the *i*-th segment are presented. The torques were calculated from the assessed finger joint positions and the measured endpoint force (f_s) using a recursive computational method.

the segment i. The torque vector ${}^kT_{i-1,i}$ describes the torque of the previous segment onto the segment i. ${}^kT_{i,i+1}$ is the torque vector of the next segment acting on the segment i. The vector product ${}^kr_{gi} \times {}^km_ig$ describes the effect of gravity force and ${}^kr_{fi} \times {}^kf_{i-1,i}$ represents the torque caused by the force ${}^kf_{i-1,i}$ acting around the origin with the moment arm ${}^kr_{fi}$ (Fig. 4). The distance vectors used were calculated from the locations of the markers, expressed in the sensor coordinate system.

Next, the force ${}^kf_{i-1,i}$ and the torque ${}^kT_{i-1,i}$ are derived from the above equations. In the first step of the recursive computation (i = 3), the negative force ${}^kf_{i,i+1}$ equals the grip force f_s measured with the force sensor and ${}^kT_{i,i+1}$ equals zero since the fingertip is not attached to the object surface (Fig. 4):

$$\begin{aligned} {}^kf_{3,4} &= -f_s \\ {}^kT_{3,4} &= 0 \end{aligned} \qquad \text{(Eq. 3)}$$

The force and torque vectors of the distal joint (i = 2) are calculated from the fingertip force:

$$\begin{aligned} {}^kf_{2,3} &= {}^kf_{3,4} - {}^km_3g \\ {}^kT_{2,3} &= -{}^kr_{g3} \times {}^km_3g + {}^kr_{f3} \times {}^kf_{3,4} \end{aligned} \qquad \text{(Eq. 4)}$$

Next, the force and torque vectors of the medial joint (i = 1) are calculated:

$$\begin{aligned} {}^kf_{1,2} &= {}^kf_{2,3} - {}^km_2g \\ {}^kT_{1,2} &= {}^kT_{2,3} - {}^kr_{g2} \times {}^km_2g + {}^kr_{f2} \times {}^kf_{1,2} \end{aligned} \qquad \text{(Eq. 5)}$$

Finally, the force and the torque acting on the proximal joint (i = 0) are determined:

$$\begin{aligned} {}^kf_{0,1} &= {}^kf_{1,2} - {}^km_1g \\ {}^kT_{0,1} &= {}^kT_{1,2} - {}^kr_{g1} \times {}^km_1g + {}^kr_{f1} \times {}^kf_{0,1} \end{aligned} \qquad \text{(Eq. 6)}$$

The same calculations (Eqs. 3–6) are repeated for the opposite finger (k = 2) while considering the end point force vector to be oriented in the opposite direction. The calculated force and torque vectors are expressed in the sensor coordinate system. In order to obtain the torques acting in the center of each joint, we must transform the calculated vectors to the corresponding joint coordinate systems using homogenous transformations (20) defined with the placement of the joint coordinate systems.

Experiments

A right-handed healthy male individual performed the precision grip nipper pinch. The subject's

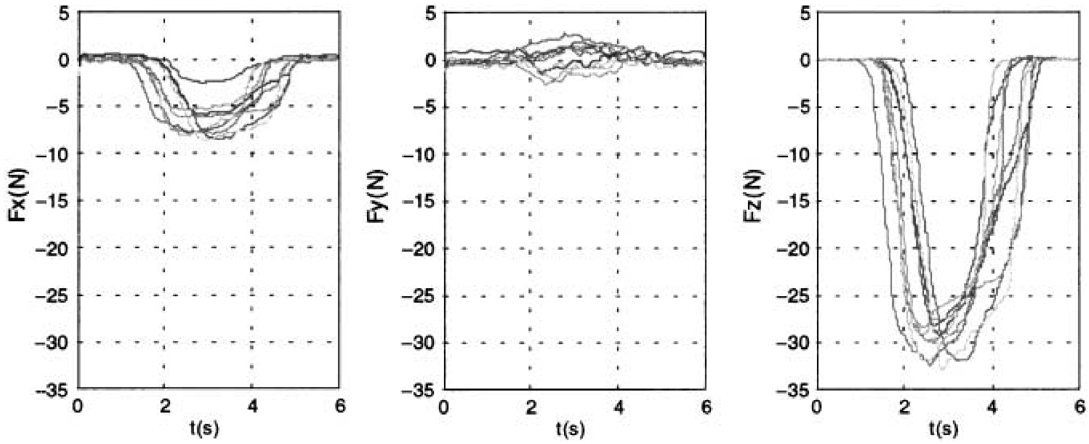

Figure 5. The force components of the grip force vector in nippers pinch as assessed in a healthy subject. The maximal force component which is perpendicular to the surface normal has a bell-shaped profile with the mean value of 30.4 ± 1.6 N within trials. The magnitudes of the other two components of the grip force vector are considerably lower. The repeatability of the results is high in *z*- and *x*-direction but low in the *y*-direction.

hand was equipped with 11 infrared markers as described in the previous section. During the experiment the grip-measuring device was attached at the edge of the table and the subject was seated on a chair located in front of the OptoTrak cameras. Two sets of cameras situated in the opposing direction were used to capture the position of all markers. The subject's forearm rested on a support with a 90° flexion of the elbow and a neutral position of the shoulder (10). The support of the forearm prevented unwanted disturbances on the grip force measurement (eg, subject's leaning onto the device). The subject was instructed to perform the precision grip on the measuring stick with low (under 20 N), medium (20–40 N), and high level force (above 40 N), keeping it steady for a moment and then slowly releasing the grip. The whole session lasted approximately 6 s. Subject had no visual feedback of the grip performed. In some cases the OptoTrak data were missing or the applied force was too low or too high with respect to the instructed force range. After the subject adjusted to the experiment procedure, 10 consecutive trials of the medium grip force were recorded and are analyzed in the paper.

RESULTS

The measured OptoTrak data of the observed grip are presented in Fig. 1 as a three-dimensional model in lateral and dorsal view of the hand coordinate system. The wire frame image reflects the posture of the hand and the position of the finger joints that are used in the recursive calculation.

The assessed grip forces during the 10 trials performed are presented in Figure 5. The grip forces shown have bell-shaped profiles along the *z*-axis of the sensor coordinate system, reaching the maximal value around 30 N. The magnitudes of the other two components of the grip force vector are considerably lower. The tangential force in the *x*-direction is negative and also reflects a bell-shaped profile. The correlation between the shapes of the two forces is very high in all trials (the average correlation coefficient c_f between the measured signals is 0.98). The force control acts mainly in the perpendicular direction to the finger pads. The results indicate that the pinch force vector is slightly rotated from normal at the point of contact to the negative *x*-axis along the tangent of the surface. This is most likely caused by the oppositional role of the thumb. In the opposition between the index finger and thumb, the two finger pads are not coplanar; therefore the thumb produces also a tangential force component to the object surface. Comparing the results of all trials (Fig. 5, Table 1) shows a significant correlation ($p < 0.01$, Pearson Correlation Coefficient is 0.791) between the peak values of the F_z and F_x force components, indicating a good repeatability of the measured pinch force. The remaining force component F_y shows more arbitrary profile. There

Table 1. The Peak Values of the Measured Grip Forces and the Corresponding Finger Joint Torques as Assessed in 10 Consecutive Trials in One Subject[a]

	Applied grip force (N)			Joint torques of thumb (Nm)				Joint torques of index finger (Nm)			
Trial	F_x	F_y	F_z	$^1T_{1y}$	$^1T_{1z}$	$^1T_{2z}$	$^1T_{3z}$	$^2T_{1y}$	$^2T_{1z}$	$^2T_{2z}$	$^2T_{3z}$
1	–5.9	–1.2	–29.0	–0.66	3.31	1.73	0.79	–0.04	2.30	0.95	0.38
2	–2.5	–0.5	–28.2	–0.26	3.15	1.27	0.59	–0.22	2.28	1.07	0.46
3	–8.5	–1.1	–32.1	–0.92	3.57	1.94	0.91	–0.00	2.63	1.21	0.54
4	–7.7	0.6	–31.7	–0.83	3.53	1.85	0.87	–0.05	2.62	1.22	0.55
5	–7.9	0.5	–29.8	–0.49	3.47	1.84	0.86	–0.19	2.58	1.13	0.51
6	–6.2	–0.8	–28.8	–0.46	3.27	1.67	0.79	–0.16	2.49	1.12	0.51
7	–5.5	2.4	–29.4	–0.28	3.47	1.63	0.73	–0.23	2.47	1.02	0.46
8	–8.2	–1.9	–32.3	–0.47	3.84	1.85	0.84	–0.20	2.74	1.15	0.52
9	–8.6	–1.6	–32.4	–0.58	3.78	1.83	0.85	–0.17	2.79	1.19	0.54
10	–7.7	0.4	–29.5	–1.00	3.31	1.71	0.79	–0.14	2.41	1.05	0.48
Mean	**–6.9**	**–0.31**	**–30.4**	**–0.56**	**3.47**	**1.73**	**0.80**	**–0.14**	**2.53**	**1.11**	**0.50**
SD	(1.9)	(1.3)	(1.6)	(0.26)	(0.22)	(0.19)	(0.09)	(0.08)	(0.17)	(0.09)	(0.06)

[a] The maximal values of the grip force components F_x and F_z have low standard deviation (SD) showing that the direction of the grip remains similar between the trials. The values of the finger joint torques indicate that the total load in the proximal joint of the thumb is considerably higher than in the joint of the index finger

is no significant correlation between F_y and F_z force components ($p > 0.05$).

The recursive computation was used with the assessed grip force and finger joint positions to obtain the joint torques (Fig. 6). The four torques, which apply to the described static model, were calculated for each finger: the torque ($^kT_{1y}$) around the adduction-abduction axis of the proximal joint and the three torques ($^kT_{1z}$, $^kT_{2z}$, $^kT_{3z}$) around the flexion-extension axes. The joint torques assessed in the thumb correspond to the carpo-metacarpal (CMC), metacarpo-phalangeal (MCP), and interphalangeal (IP) joints. The torques for the index finger describe the load in the metacarpo-phalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints.

The peak values of the measured grip force and corresponding finger joint torques obtained in each trial are gathered in Table 1. The subject was able to produce similar grip force levels in all trials where the average force in *z*-direction was 30.4 ± 1.6 N. Comparing the peak torque values (Table 1) indicates that the total load in the proximal joint of the thumb is considerably higher than in the joint of the index finger ($p < 0.01$, paired-samples *t*-test). The load in the abduction-adduction axis of the index finger in the observed precision grip is lower than for the thumb. The deviations of the assessed abduction-adduction torques in the proximal joints are high which indicates that the placement of the proximal coordinate system of a finger is more sensitive to errors.

DISCUSSION AND CONCLUSION

The purpose of this study was to present a method for the static analysis of a two-fingered precision grip. The OptoTrak system was used to capture the hand posture along with the grip-measuring device aimed to simultaneously measure the grip forces. A three-dimensional model of the hand was obtained from the measurements, showing that the optical measuring system can be helpful in the analysis of hand posture. The optical method of assessing the finger positions allows unrestrained movement and grasping of objects, providing the necessary parameters for the static analysis of the grip. The accuracy of the method depends on the accuracy of the placement of the markers onto the fingers to mark the centers of joints. The finger joint positions were assessed from the joint lines on the palmar side of the hand and corrected based on the observed flexion-extension of the finger. The assessment of the proximal joint position was found to be more sensitive to errors.

The finger joint torques were calculated from the assessed finger positions and grip force utilizing the recursive calculation method. The presented joint torques describe the amount of load

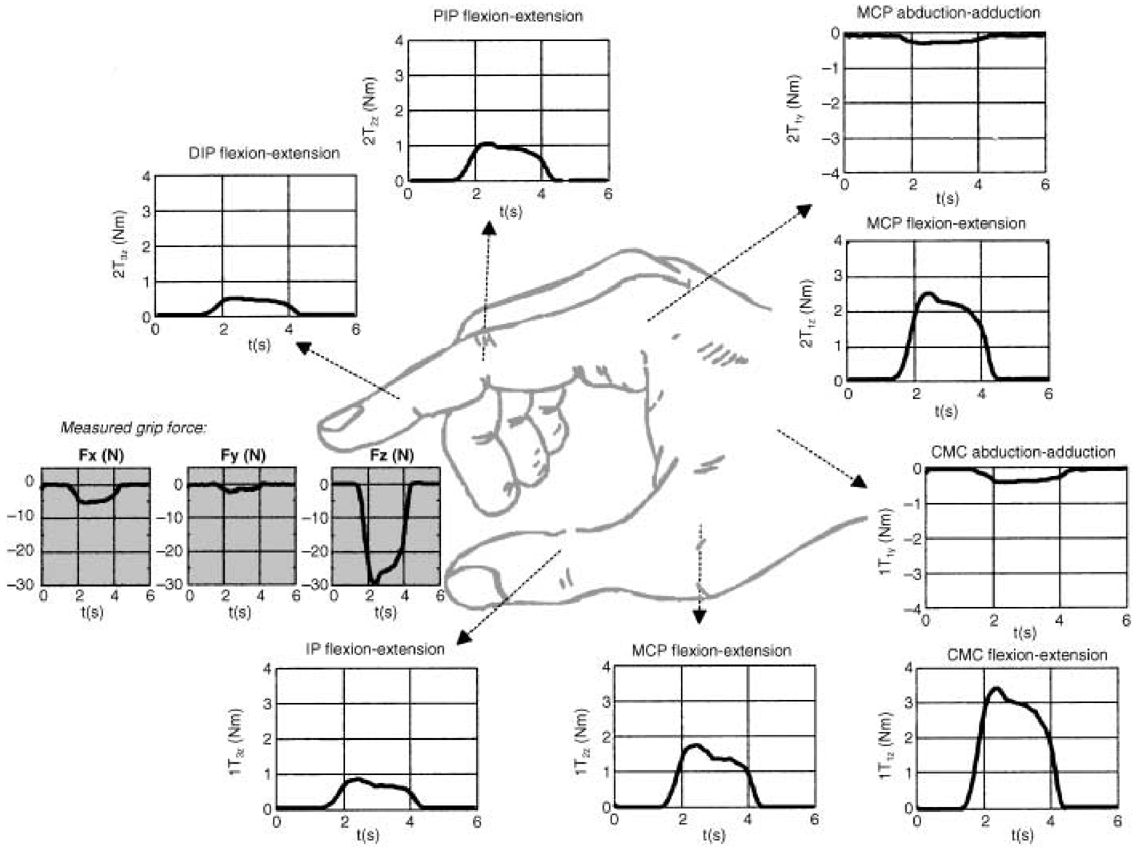

Figure 6. The measured grip force in nippers pinch and the calculated finger joint torques. The grip force has a bell-shaped profile with the peak value in the perpendicular direction to the measuring object. The torque values indicate the load on the finger joints during the observed grip.

on the joints during the grip applied. In this paper a set of 10 trials for one subject is presented. Analysis of subject-to-subject variations will be included in our future investigations.

During the experiment the subject relied on his proprioceptive feedback and had no visual information on the performance of the grip. This resulted in some diverse results in the grip force levels and duration of the grips before the subject became accustomed to the experiment procedure. Adding some additional feedback information (eg, on the duration of the trial and/or the force level reached) could improve the repeatability of the measurements and allow increased correlation of data in experiments with more subjects, who could more easily apply force levels required by the examiner. The grip-measuring device also could be used as an input device for an isometric tracking task (21) where the subject would be presented with a graphic display of the target signal and the measured grip force response. The assessment of isometric grip forces by the grip-measuring device and visual feedback from the computer screen could offer useful results for the analysis of sensory-motor control of the grip force in different grip configurations (21).

The proposed method is similar to the part of the Fugl-Meyer hand evaluation test (1) used in hemiplegic patients where the subject is asked to perform a precision grip of a pencil. With a modification of the grip-measuring device, grasps of different objects could be simulated. Differently shaped endpoint objects (eg, in the shape of a disk, sphere, cylinder, etc.) could replace the measuring stick in order to determine the forces that act on such objects in different hand postures. Such a method can be used in connection with different rehabilitation therapies, including functional electrical stimulation (FES) (2,3), to follow the improvement of a patient's condition or to train the subject in grip force control. The knowledge of forces acting on differently shaped objects is also important in ergonomics where different products and tools need to be adjusted to the human grip to minimize discomfort and injury (16).

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Appendix B: Clinical Biomechanics, 2004

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Force tracking system for the assessment of grip force control in patients with neuromuscular diseases

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Abstract

Background. The majority of hand functionality assessment methods consist of the maximal voluntary grip force measurement. Additional knowledge on sensory-motor control can be obtained by capturing functional grip force in a time frame. Tracking methods have been successfully used for the assessment of grip force control in stroke patients and patients with Parkinson's disease.

Methods. A novel tracking system for the evaluation of grip force control is presented. The system consists of a grip-measuring device with the end-objects of different shapes which was used as input to a tracking task where the patient applied the grip force according to the visual feedback. The grip force control was assessed in 20 patients with neuromuscular diseases and 9 healthy subjects. The performance of two tracking tasks was analysed in five grips. The ramp-tracking task was designed to assess the grip strength and muscle fatigue. The sinus-tracking task was used to evaluate grip force control during periodic muscle activation.

Findings. The results suggest that in some patients the disease did not affect their grip force control despite evident muscular weakness. Most patients produced larger tracking errors in precision grip while the healthy subjects showed less significant differences in performance among the grips tested.

Interpretation. The current study investigated force control in patients with neuromuscular diseases where detection of small changes in motor performance is important when following the progress of disease. The presented evaluation method can provide additional information on muscle activation and fatigue as compared to traditional grip strength testing.

Keywords: Grasp; Hand; Grip strength; Neuromuscular diseases; Sensory motor performance

1. Introduction

Grasping and manipulation of objects require an accurate grip force control to comply with the requirements of the task and properties of the object (e.g. shape, weight, friction) (MacKenzie and Iberall, 1994). Accurate grip force control is essential in performing activities such as grasping of fragile objects, resistance to external forces (e.g. holding a spoon to resist gravity), and when applying movement to the object (e.g. turning a knob) (MacKenzie and Iberall, 1994).

An injury to a central nervous system, hand injury or disease can affect neuromuscular system involved in grasping, resulting in reduced hand functionality when performing daily activities (Fugl-Meyer et al., 1975; Hermsdörfer et al., 2003). Hand functionality tests used in clinical practice (Fugl-Meyer et al., 1975; Jebsen et al., 1969) consist of picking and using different objects to accomplish selected tasks while the performance is either timed or evaluated by therapist. Computer assisted methods can greatly increase the accuracy and objectivity of the assessment while reducing the examination time and resources. The information on hand functionality is often obtained indirectly by assessing the range of motion of the fingers and wrist, grip strength and

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hand dexterity (Marx et al., 1999; McPhee, 1987). The available grip strength measurements are predominantly focused on the assessment of the maximal voluntary grip force providing information only on short-duration muscle strength (Smith, 2000). The daily activities, that involve manipulation of different objects, mostly require sub-maximal forces; therefore the assessment of the maximal voluntary grip force reflects only partial information on the hand functionality (McPhee, 1987). The grip strength is usually assessed using different mechanical dynamometers that measure the intensity of the applied grip force but no information is obtained on the dynamics and direction of the force (Innes, 1999). The dynamometers used are often not suitable for accurate measurements of low-level grip forces (typically found in patients with neuromuscular diseases) because their measurement range is too large with respect to the force applied (Innes, 1999). The measurement approach can be improved by introducing electronic dynamometers allowing real-time measurements of the grip force providing the clinician with a force–time curve (Kamimura and Ikuta, 2001). Various instrumented objects have also been proposed to assess the dynamic grip forces acting on the objects which are in shape and size similar to real objects used in daily activities (Memberg and Crago, 1997; McGorry, 2001).

In the paper we present an original grip-measuring device with differently shaped measuring objects with the aim to assess the forces in different hand postures. The grip-measuring device was used in connection with a grip-force tracking task for the evaluation of grip force control in patients with neuromuscular diseases. In the tracking task a person applied the grip force according to the visual feedback on the target signal while minimising the difference between the target and actual response. Tracking tasks have been used previously to study the sensory-motor functions (Sharp and Newell, 2000) and the development of grasping in human (Blank et al., 2000), to assess the coordination of grip force in patients with Parkinson's disease (Vaillancourt et al., 2001), as a therapy for hemiplegic patients (Kriz et al., 1995) and to evaluate the grip force control in healthy persons (Kurillo et al., 2002). The aim of our study was to present a novel method for the evaluation of the grip force control in patients with neuromuscular diseases where the quantification of the muscular weakness and hand functionality is essential to evaluate the progress of the disease (Zupan, 1996).

2. Methods

2.1. Participants

We analysed the grip force control in 20 patients with neuromuscular diseases (mean age 35.7 (SD 11.4) years), 13 of them were female and 7 were male. The control group consisted of 9 healthy male volunteers (mean age 28.4 (SD 3.4) years). All participants reported right-hand dominance. Prior to the investigation, all subjects were informed of the test procedures and gave consent to participate. The study was approved by the ethics committee of Institute of Rehabilitation, Republic of Slovenia.

2.2. Grip-measuring device

A grip-measuring device (Fig. 1) was constructed to measure the forces of different grips. The instrument developed is based on the force transducer JR3 (JR3, Inc., Woodland, USA) which can provide information on the grip strength and direction of the force (Kurillo et al., 2003). The measurement range of the sensor is 110 N in the horizontal directions and 220 N in the vertical direction. The sensor is attached to a metal construction allowing the transfer of forces from the point of contact to the sensory unit. The grip-measuring device can be fitted with different end-objects which are in shape and size similar to objects used in daily living, such as a pencil, thin plate, ball and cylinder (Fig. 1).

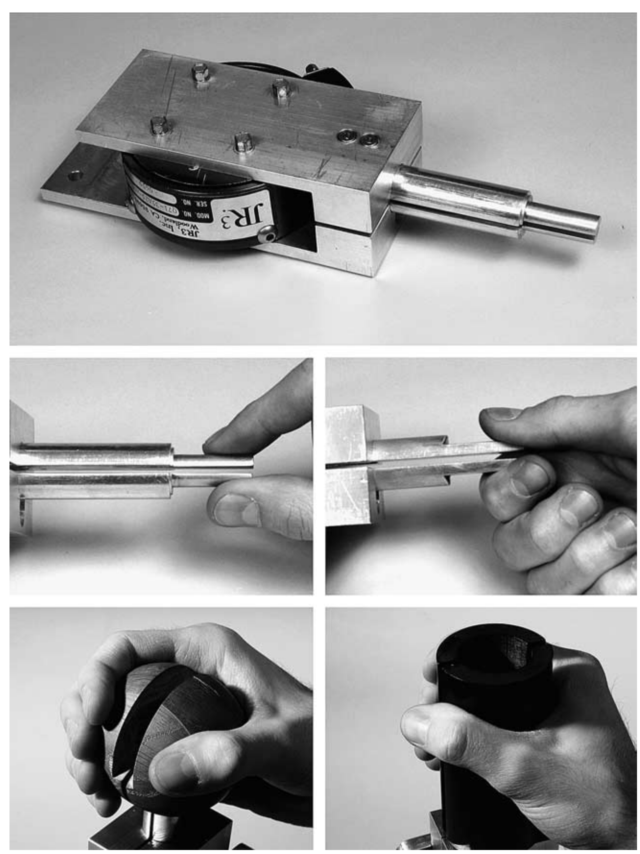

Fig. 1. A grip-measuring device with different end-objects was designed to assess forces in grips used in daily activities (e.g. nippers pinch, spherical, lateral and cylindrical grip).

Each measuring object is divided into two symmetrical halves that shape into a full object when attached to the device. The selection and the physical size of the objects were based on the Fugl-Meyer hand evaluation method (Fugl-Meyer et al., 1975). The grip-measuring device was calibrated by placing different weights at the point of contact (Kurillo et al., 2003). The device can measure forces up to 100 N with non-linearity of 1.4%. The resolution of the measured grip force is about 0.03 N.

2.3. Force tracking task

The basic scheme of the grip-force tracking system is presented in Fig. 2. The goal of the tracking task was to track the presented target as accurately as possible by applying the appropriate grip force to the end-object of the grip-measuring device. The target signal was indicated in blue colour and the force response in red colour. Vertical position of a blue ring, located in the centre of the screen, corresponded to the current value of the target and the position of a red spot corresponded to the applied grip force in real-time. The red spot moved upwards when the force was applied to the measuring object and returned to its initial position when the grip was released. The aim of the tracking task was to continuously track the position of the blue ring by dynamically adapting the grip force. The tracking task was programmed in Matlab–Simulink (The MathWorks, Inc., Natick, USA). The force applied to the grip-measuring device was sampled with the frequency of 100 Hz. The feedback signal was filtered in real-time with a 2nd order Butterworth filter (cut-off frequency 12 Hz). The complexity of the tracking task was adjusted by selecting the shape of the target signal (e.g. ramp, sinus, rectangular shape), setting the level of the required grip force and changing the dynamic parameters of the target (e.g. frequency, speed).

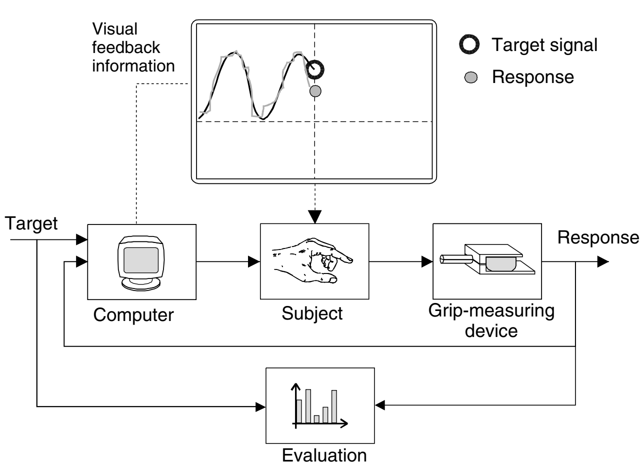

Fig. 2. The aim of the tracking task is to track the presented target as accurately as possible by applying the appropriate force to the grip-measuring device. The shape (e.g. ramp, sinus, rectangular shape), level (i.e. required grip strength) and the dynamics (e.g. frequency, speed) of the target are set individually on the computer. Evaluation of the grip force control is then performed by analysing the difference between the target and measured response.

2.4. Procedures

The tracking performance was assessed in five different grips: cylindrical, lateral, tip and nippers pinch and spherical grip, evaluating the dominant and non-dominant hand. Two different tracking tasks were selected for the evaluation of the grip force control. The first task consisted of tracking a ramp target which increased in 15 s from the initial value of 0 N to the final value of 30 N for nippers pinch, 60 N for lateral and 70 N for spherical and cylindrical grips. The peak values for each grip were selected based on our preliminary investigation involving patients with neuromuscular diseases and correspond to about 30% of the maximal voluntary grip force in healthy subjects (Mathiowetz et al., 1985). The patient was instructed to track the target as long as possible and, if unable to exert the required force, to keep the grip until the end of the trial. The trial lasted 32 s. The second task consisted of tracking a sinusoidal target with the frequency of 0.2 Hz. The amplitude of the signal was set at about 30% of the patient's maximal grip force as assessed in the ramp trial. The patient was asked to follow the moving target as accurately as possible by applying an appropriate force to the grip-measuring device.

During the test the patient was sitting in a wheelchair in front of the computer screen, with the forearm secured to a hand-support. For the maximal performance of the grip, the elbow was positioned in a 90° flexion and the shoulder was in a neutral position. The grip-measuring device was secured using a vice to prevent any movements or disturbances during testing. The patient was asked to maintain consistent grip while performing the task and was not allowed to use 'trick' movements (e.g. influencing the grip force by changing arm orientation or leaning onto the device). A therapist monitored the patient's hand posture and the test was repeated if the patient did not follow the requested procedure. The patient first performed one test trial of the tasks and then two trials of each tracking task were recorded for each grip type. The more accurate performance of the two trials was considered in further analysis. Our previous study in healthy subjects (Kurillo et al., 2002) showed low variability of the tracking results between repeated trials. The rest period between consecutive trials was 45 s. When changing grips, the person rested about 2 min. All the tasks were performed on the same day. The same procedure was followed for the control group of healthy subjects.

2.5. Data analysis

We quantified the ramp task by calculating the average maximal grip force sustained for the duration of 5s at the point where the target signal reached the maximal value (time interval 17–22 s). The results of the ramp task were used to adjust the amplitude of the sinus task aiming to suit the patient's strength abilities.

We assessed the performance of the sinus task by calculating the relative root mean square error (rrmse) between the target F_T and the measured output force F_O over the trial time T (Jones, 2000):

$$\text{rrmse} = \sqrt{\frac{1}{T}\sum_{t=2\text{ s}}^{T=32\text{ s}} \frac{(F_O(t) - F_T(t))^2}{\max(F_T)^2}} \quad (1)$$

The tracking error was normalised by the maximal value of the target signal to allow comparison among the results obtained in different grips and patients. A lower tracking error suggests better activation control of the corresponding muscles and improved hand functionality (Kriz et al., 1995).

The dynamic characteristics of the grip force were further assessed by analysing the coordination of tracking, which is described by the measured force $F(t)$ and calculated time derivative (i.e. force rate) $\mathrm{d}F/\mathrm{d}t$ (Jones, 2000). The trajectory obtained was plotted in the force–velocity domain, where the x-axis represented the force and the y-axis the force rate. For the sinusoidal target the normal grip force response results in a smooth circular trajectory. Producing non-smooth response during the increase or decrease of the grip force due to reduced muscle control results in deviations from the circular plot. The grip force coordination was quantified by the coefficient of coordination (K_c), defined by the correlation between the target signal and force response and the correlation of the corresponding time-rates, where the value closer to one suggests more enhanced coordination of the grip force:

$$K_c = \text{corrcoeff}(F_T, F_O) \cdot \text{corrcoeff}\left(\frac{\mathrm{d}F_T}{\mathrm{d}t}, \frac{\mathrm{d}F_O}{\mathrm{d}t}\right) \quad (2)$$

2.6. Statistical analysis

Two functional groups of patients were identified from the tracking results of the sinus task using k-means clustering algorithm (García and Gordaliza, 1999). For each group, mean tracking errors and variability of the results were analysed. One-way analysis of variance for group samples was used to compare the results among groups. We considered P-values of 0.05 or less as statistically significant. The statistical analysis was performed with SPSS software (Lead Technologies, Inc., Chicago, USA).

3. Results

3.1. Ramp task

The maximal force level reached in the ramp task was used to quantify the strength of individual patient in different functional grips when gradually increasing the force. Fig. 3 shows the results of the ramp test as performed by a healthy subject (S7) and two patients (P15 and P16) while using lateral grip of the right hand. The healthy subject was able to accurately track the ramp target without large deviations and showed no fatigue during the trial. The two patients performed the task with much larger deviations from the target signal. The patient P15 was able to track the target while increasing but was unable to retain the exerted grip force until the end of the trial. The decrease of the force was about 35% of the maximal exerted force on the interval of 15 s. The patient P16 showed large deviations when increasing the grip force. The force level reached in the lateral grip was about 45 N, representing 75% of the required level for this test. The decrease of the grip force due to muscle fatigue is evident in the results of both patients.

3.2. Sinus task

The performance of the sinus task was assessed by calculating the relative tracking error between the target and measured force (Eq. (1)). Fig. 4 shows the results of the tracking in lateral grip as obtained in the healthy subject (S7) and two patients (P15 and P16). The healthy subject accurately followed the target (rrmse = 0.45) and produced a smooth response with small deviations. Comparing the results between the two patients showed that the patient P16 had more difficulty adapting the

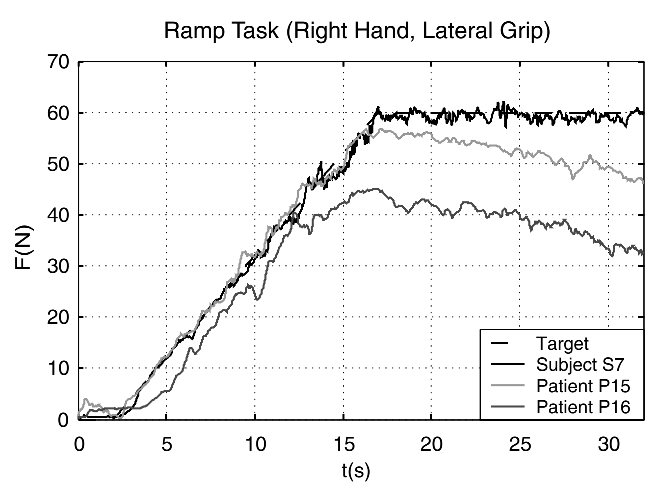

Fig. 3. The results of the ramp task as assessed in healthy subject S7 and patients P15 and P16 when using lateral grip of the right hand. The task was used to assess grip strength values for each subject.

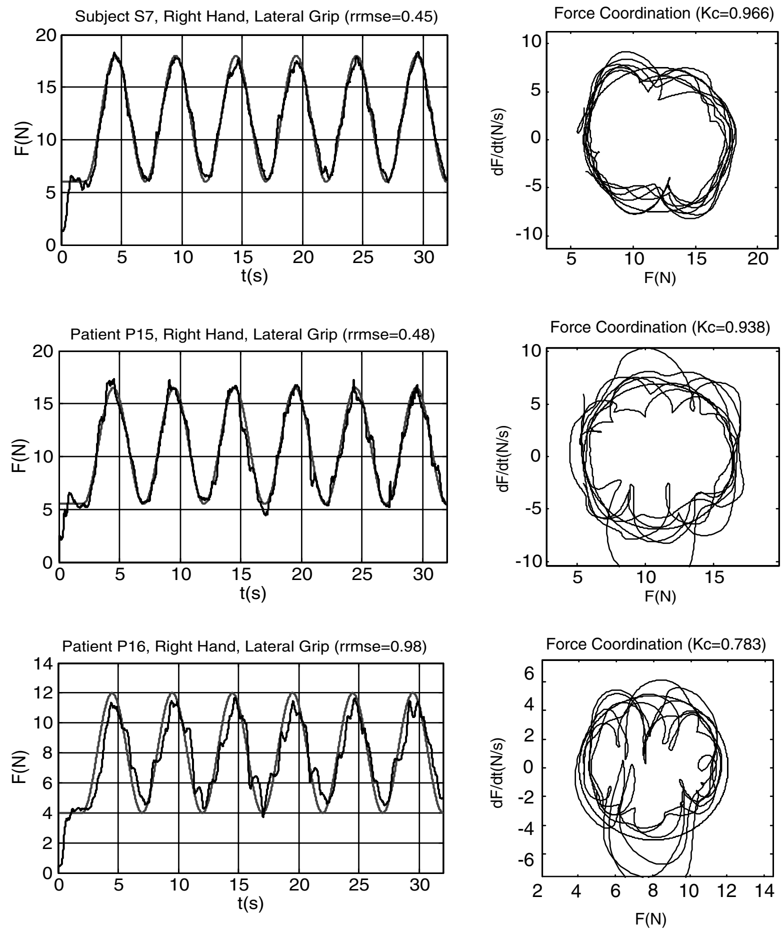

Fig. 4. The results of the sinus task as assessed in healthy subject S7 and patients P15 and P16 when using lateral grip. The measured response with respect to the target is shown on the left and the corresponding trajectory in the force–velocity space is shown on the right side.

grip force to the target and produced much higher tracking error (rrmse = 0.98) than patient P15 (rrmse = 0.48). The grip force response of the patient P16 reflects more abrupt muscle activation patterns that unable the patient to gradually increase or decrease the grip force.

The corresponding trajectory in the force–velocity domain is presented in Fig. 4 (on the right) showing the circular trajectory of the target and the trajectory of the measured grip force. The coordination of tracking was quantified by calculating the coefficient of coordination K_c (Eq. (2)). The two patients P15 ($K_c = 0.938$) and P16 ($K_c = 0.783$) produced less smooth response as compared to the healthy subject S7 ($K_c = 0.966$). The results of the patient P16 show more irregular trajectory due to abrupt changes of the grip force when tracking the sinusoidal target. Both patients used excessive force rates when increasing or decreasing the force.

The results of the tracking error varied significantly among the patients, therefore we tried to identify functional groups of patients with similar tracking performance. We analysed the tracking results of the sinus task in all grips when using the dominant and non-dominant hand. The results showed that some of the patients produced tracking errors in the range of the healthy subjects while others produced more than twice as large tracking errors. We applied k-means clustering algorithm (García and Gordaliza, 1999) to group the patients by their grip force control. Two clusters were identified from the results of all tests and each patient was grouped based on his/her average tracking error. The first cluster was denoted as "group A", containing 11 patients with larger tracking errors and the second cluster was denoted as "group B", containing 9 patients with lower tracking errors.

In Fig. 5 the average tracking errors and the average coordination coefficients as assessed in the two groups of patients are compared to the results of the healthy subjects. The patients in group A produced on average about twice as large tracking errors (non-dominant hand: 1.10 (SD 0.25), dominant hand: 1.15 (SD 0.29)) as compared to the patients in group B (non-dominant hand: 0.64 (SD 0.14), dominant hand: 0.66 (SD 0.16)) and healthy subjects (non-dominant hand: 0.53 (SD 0.16), dominant hand: 0.52 (SD 0.17)). In both groups

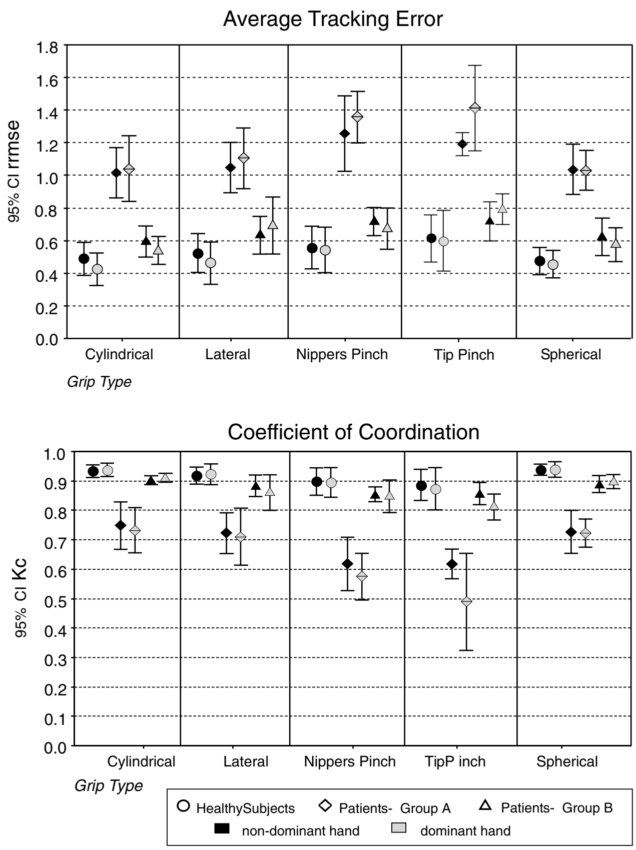

Fig. 5. The average tracking error (rrmse) and coefficient of coordination (K_c) as assessed in the healthy subjects and the two groups of patients (A and B). The charts show mean values with confidence interval (CI) of 95%.

of patients slightly larger differences in tracking error among the grips can be observed for the dominant hand. The results of both groups indicate that most patients produced larger tracking errors in nippers pinch or tip pinch as compared to the other grips (Fig. 5). Both groups of patients show significant effect of the grip type on the tracking accuracy in the dominant hand but no significant effect was found in the non-dominant hand (one-way ANOVA, non-dominant hand: $F_{4,48} = 2.221$, $P = 0.81$, dominant hand: $F_{4,48} = 4.867$, $P = 0.002$; group B: non-dominant hand: $F_{4,40} = 1.291$, $P = 0.290$, dominant hand: $F_{4,39} = 3.193$, $P = 0.023$). The tracking results of the healthy subject were not influenced by the grip type used (non-dominant hand: $F_{4,40} = 0.812$, $P = 0.525$, dominant hand: $F_{4,40} = 1.175$, $P = 0.337$). Comparing the average tracking results of the two patient groups to the healthy subjects showed significant difference in performance of the task (group A: $F_{1,194} = 334.4$, $P < 0.0001$, group B: $F_{1,177} = 28.72$, $P < 0.0001$). The tracking error results in Fig. 5 suggest that the patients from group B have more enhanced muscle control because they could perform the task in all tested grips with similar accuracy as the healthy subjects.

The analysis of the average coordination coefficient (K_c) showed significant differences between the two patient groups and the healthy subjects (group A: $F_{2,195} = 220.2$, $P < 0.0001$, group B: $F_{2,177} = 24.98$, $P < 0.0001$). The average coordination coefficient of the healthy subjects was 0.915 (SD 0.049) for the dominant hand and 0.915 (SD 0.062) for the non-dominant hand. The results of the patient group B (dominant hand: 0.869 (SD 0.066), non-dominant hand: 0.879 (SD 0.042)) reflect higher coordination of the grip force as compared to group A (dominant hand: 0.652 (SD 0.169), non-dominant hand: 0.691 (SD 0.120)). The results of patients show significant effect of the grip type on the force coordination (group A: non-dominant hand: $F_{4,48} = 3.370$, $P = 0.016$, dominant hand: $F_{4,48} = 5.930$, $P = 0.001$; group B: non-dominant hand: $F_{4,40} = 2.741$, $P = 0.042$, dominant hand: $F_{4,39} = 4.125$, $P = 0.006$). No significant effect of the grip selection was found in healthy subjects (non-dominant hand: $F_{4,40} = 2.001$, $P = 0.113$, dominant hand: $F_{4,40} = 2.130$, $P = 0.095$), which suggests that the muscle groups in healthy subjects more accurately adjust the dynamics of the exerted force while performing the tracking task.

4. Discussion

In the present study we presented a grip-force tracking system for the evaluation of the grip force control. The proposed tracking system consists of a grip-measuring device which was used to measure the grip force while grasping the objects similar to objects used in daily activities. The device can assess the force with much greater accuracy as compared to the commonly used mechanical dynamometers and allows real-time computer assisted measurements of the applied force.

Precise evaluation of hand function in the progressive neuromuscular diseases is important when following the changes in muscular weakness. The degree by which different muscles are affected by a neuromuscular disease is linked to the form of the disease and the onset of the condition. It is important to note that large differences in muscular strength and functional state can be observed also between patients with the same form of the disease. The results of clinical tests in patients with neuromuscular diseases should therefore be considered on individual basis (Zupan, 1996). In our study we examined the performance of two tracking tasks in 20 patients with neuromuscular diseases to demonstrate the use of the tracking system for the evaluation of grip force control. The ramp task allows quantification of the muscular strength and muscle fatigue which can be used to follow the progress of disease. The results of the sinus task showed that the method can provide information on muscle activation patterns during periodic muscle contraction. Comparing the results of tracking with a group of healthy subjects suggests that in some patients the disease did not affect their grip force control despite the evident muscular weakness. Most patients produced larger tracking errors in nippers pinch and tip pinch as compared to other grips. In some patients excessive force rates when increasing or decreasing the force were observed.

The tracking task presented was easy for patients to understand and even older patients with no computer experience were able to perform the task without any difficulties. The results of our previous study in healthy subjects (Kurillo et al., 2002) showed low variability of the tracking results between repeated trials, therefore only two trials were recorded for each grip. Further study could investigate the effect of training with the tracking system in the lower functional group of patients (group A) to possibly improve their grip force control. No links between the patient's performance of the tracking tasks and diagnosis were found in this study, possibly due to the small sample group and the nature of the neuromuscular diseases, where patients with the same form of the disease can be affected to a different degree (Zupan, 1996).

The proposed method could be efficient in connection with different rehabilitation therapies (e.g. physiotherapy, functional electrical stimulation, drug treatment) to follow the influence of the therapy on patient's muscular strength and grip force control. Patient's performance can be screened before and after the applied therapy to assess its effect on the hand functionality. The cognitive information associated with the performance of the tasks can further assist the rehabilitation process by providing feedback on the rehabilitation progress to the patient. We believe that the tracking system can also be applied as a training assistive device where the difficulty of the tasks should be increased throughout the therapy promoting in this way patient's hand dexterity and grip force control.

5. Conclusions

In summary, the results of our study in patients with neuromuscular diseases showed that in some patients the disease significantly affected their grip force control in addition to the muscular weakness evident in all patients tested. Compared to healthy subjects, many patients produced much larger tracking errors in precision grips which require more accurate muscle control. Some of the patients used excessive force rates when tracking the sinusoidal target.

The presented evaluation method can provide additional information on muscle activation and fatigue as compared to traditional grip strength testing. More accurate measurements of the grip force in a time frame allow easier detection of changes in muscular strength and sensory-motor functions. Further studies in groups of patients with a particular form of neuromuscular disease are needed to obtain more information on the reduction of the grip force control during the course of the disease.

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Grip force tracking system for assessment and rehabilitation of hand function

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Abstract. The aim of the paper is to present a novel tracking system for the assessment and training of grip force control. The system consists of two force measuring units of different shapes, which can be connected to a personal computer for visual feedback and data acquisition. We present the results of the assessment of the grip force control in 32 healthy subjects of different age groups and preliminary results obtained in a patient after head-injury who was treated with Botulinum-Toxin for hand spasticity. The proposed tracking system was also applied as a training tool in 10 post-stroke patients to possibly improve their grip force control. The results in healthy subjects showed significant differences in grip force control among different age groups. In the patient after Botulinum-Toxin treatment the method revealed noticeable effects of the therapy on the patient's tracking performance. Training with the tracking system showed considerable improvements in the grip force control in 8 out of 10 stroke patients. The proposed tracking method is aimed to be used in connection with different rehabilitation therapies (e.g. physiotherapy, functional electrical stimulation, drug treatment) to follow the influence of the therapy on patient's muscular strength and grip force control.

Keywords: Grasp, grip strength, hand, sensory motor performance, stroke rehabilitation

1. Introduction

An injury to a central nervous system, hand injury and neural or neuromuscular disease can often result in reduced hand function when performing daily activities. Different rehabilitation programmes are applied to restore patient's hand function. Objective and accurate assessment is needed to monitor and quantify patient's progress during the therapy and to validate the effects of the treatment [19]. The majority of hand function tests use qualitative or semi-quantitative measures to evaluate patient's functional state of the hand [5,11]. A number of such tests lack the objectivity and accuracy to be able to detect small changes in performance [18,19], reducing in this way the ability to more specifically adjust the therapy to the current condition of the patient.

Grip strength measurements are often included in the hand function evaluation [9]. The grip strength measurements are predominantly focused on the assessment of the maximal voluntary grip force, providing information on short-duration muscle strength [19]. The maximal grip forces are rarely used in daily

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activities, which often require more precise application and control of the grip. One of the important factors affecting the hand function is the ability to control the grip strength of sub-maximal forces which are employed during grasping and manipulation of different objects [17,23]. The classical methods for grip strength assessment using mechanical dynamometers can be improved with the use of computer assisted measurements, providing more accurate and objective results [13]. Such measurements can be performed with custom-designed instrumented objects that are in shape and size similar to objects used in daily life [9,20].

An important factor in the assessment and rehabilitation is the feedback provided to the patient on the functional condition and the performance of different tests [8]. Providing such information during or after the therapy can increase the effectiveness of the rehabilitation process [21]. This is especially important in patients where the sensory-motor functions are affected [7]. The assessment of the sensory-motor functions can be efficiently performed with tracking tasks [12]. In the tracking task a person applies the force according to the visual feedback while minimising the difference between the target and the actual response. The dynamic behaviour and range of the target can be adjusted to always maximize patient's performance. Tracking tasks have been used previously to study the development of grasping in human [1], to assess the coordination of grip force in patients with Parkinson's disease [25], as a therapy for hemiplegic patients [14] and to evaluate grip force control in patients with neuromuscular diseases [16]. The tasks can be presented in a simple desktop environment [7] or in more complex virtual environments [10].

The aim of our research was to develop an assessment tool which could be used to evaluate effects of therapy or to train patient's grip force control. Previous studies [6,7,13,25] have shown the clinical importance of grip force control assessment. The proposed application consists of a compact measuring system with two force measuring units of different shapes, which can be connected to a personal computer. The system was used in connection with a tracking task to assess the grip force control in healthy subjects of different age groups and patients with neuromuscular diseases [16]. In the paper we present preliminary measurements on a patient after head injury who was treated with Botulinum-Toxin [3] to reduce hand spasticity. The aim of the study was to obtain information on the effects of the treatment on the grip force control.

The second part of our study is focused on the use of biofeedback training for restoration of grip force control in patients after stroke. In stroke patients the ability to control and scale grip forces is greatly reduced [2]. The rehabilitation of the paretic hand consists of repetitive training of the affected muscles [4] which can be further enhanced by providing biofeedback on the exercise performance to the patient [10,27]. Biofeedback training of the sensory-motor functions can initiate reorganization of central nervous system improving the outcome of the rehabilitation [2,14,21,26]. The aim of our investigation was to employ the tracking system as a training method for a group of patients after stroke and evaluate the effects of training. The training tasks were aimed to improve the accuracy of the grip force control and enhance the ability to balance and release the grip. The patients trained over the period of four weeks in combination with the standard physical therapy.

2. Materials and methods

2.1. Grip force tracking system

The system consists of two grip-measuring devices of different shapes (cylinder and thin plate) which connect to a personal computer through an interface box (Fig. 1). Each unit is based on a single point

Fig. 1. A compact assessment system with two force measuring units in the shape of a cup and thin plate can be connected to a personal computer to accurately measure the dynamic grip force in cylindrical and lateral grip.

load cell (PW6KRC3 and PW2F-2, HBM GmbH, Darmstadt, Germany), which is mounted on a metal construction. The design of the devices was based on our previous research [15,16]. The shape and the size of the force measuring units are similar to the objects used in daily activities (e.g. a cup and a key), allowing in this way the assessment of functional gripping forces. The diameter of the measuring cylinder is 55 mm and the height is 140 mm. The sensor is mounted inside the split cylindrical housing made of hard aluminium (Fig. 1). The instrument allows the assessment of forces up to 300 N with the accuracy of 0.02% over the entire measuring range. The second device is made up of two metal parts which shape into a thin plate at the front end, resembling a flat-shaped object (e.g. a key). The area of the plate is 18×30 mm^2 and the thickness of the object is about 8 mm. The load cell used can measure forces up to 360 N with the accuracy of 0.1%.

The output from the two load cells is sampled through the interface box, consisting of an amplifier with supply voltage stabilizer and an integrated 12-bit A/D converter. The interface box connects to the parallel port of a personal computer, which is used for data acquisition and visual feedback. The sampling frequency of forces can be above 1 kHz. Additionally, six analogue signals can be measured simultaneously if required by the application (e.g. acquisition of EMG signals during the grip force measurement). For our investigation the grip force measuring system was connected to a personal computer for data acquisition and to provide visual feedback to the patient (Fig. 2). The force signal was sampled with the frequency of 100 Hz and filtered in real time by the 2nd order Butterworth filter (cut-off frequency 12.5 Hz, delay 80 ms). The delay between the input and the visual feedback, mainly originating from filtering of the signal, was below 150 ms which is the minimum time interval needed for a person to process visual information [24]. The presented task required the patient to track the target on screen by applying appropriate force to the grip-measuring device (Fig. 2). The target signal was presented with a blue ring moving vertically in the center of the screen. The applied force measured with the grip-measuring device was indicated with a red spot. When the grip force was applied, the red spot moved upwards and when the force was released, the red spot moved to the initial position. The past values of the two signals were presented as two time-varying trails (in blue and red color), which moved from the center of the screen to the left side. The aim of the task was to continuously track the position of the blue ring by dynamically adapting the grip force to the measuring unit. A graphic user interface was programmed to allow simple selection of different tracking tasks and automated data

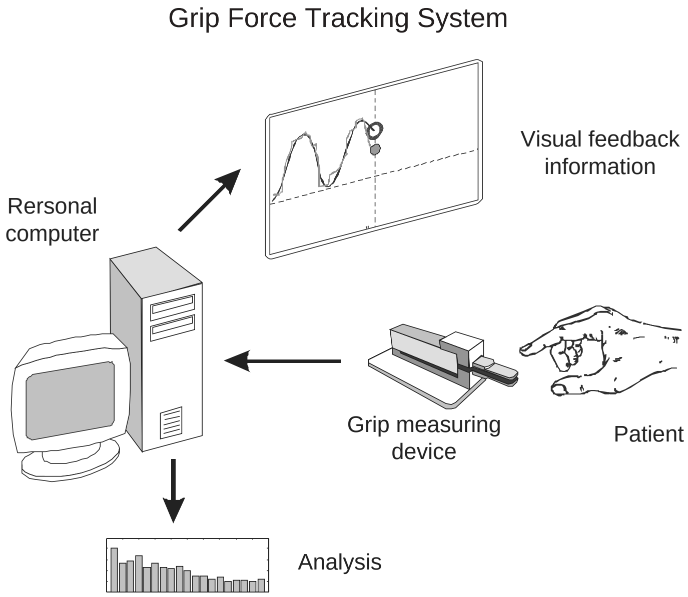

Fig. 2. Grip force control was assessed using the force tracking task where the patient applied the grip force according to the visual feedback from the computer screen.

storage. The complexity of the task was adjusted by selecting the shape of the target signal (e.g. ramp, sinus, and rectangular shape), setting the level of the target force and changing the dynamic parameters (e.g. frequency, force-rate).

2.2. Analysis

The patient's force tracking data are automatically stored after each task is performed to allow analysis of patient's performance at later time. The performance of the tracking is quantified by calculating relative tracking error between the target signal and the measured response [16]. The tracking error is normalized by the peak value of the target to allow the comparison of the results obtained at different force levels.

The variability of the results between groups was tested using one-way analysis of variance (ANOVA) for group samples. We considered P-values of 0.05 or less as statistically significant. The statistical analysis of the results was performed with SPSS software (Lead Technologies, Inc., Chicago, IL, USA).

2.3. Assessment

We investigated the grip force control in a group of 32 healthy subjects which were divided into three different age groups: 10-year old children ($n = 12$, mean age: 10 (SD 0.4) years), 25- to 35-year old adults ($n = 10$, mean age: 27.7 (SD 3.5) years) and 50- to 60-year old adults ($n = 10$, mean age: 55.6 (SD 3.1) years). The grip force control was evaluated while tracking three different targets: ramp, sinus and rectangular target. The ramp signal tracking allows quantification of the muscular strength and muscle fatigue which are particularly important in evaluation of hand function in patients with neuromuscular diseases [16]. The sinus and rectangular targets were used to evaluate dynamic characteristics of the grip force during periodic muscle activation.

During the test the subject was seated in front of the computer screen on a chair with adjustable height. The grip-measuring device was positioned at the edge of the table in the proximity of the subject's hand. The subject was asked to maintain about 90° flexion in the elbow and keep a neutral position of the shoulder. Each subject was first explained the three tracking tasks and performed one test trial of each task. For the assessment the subjects performed two trials with the ramp, three trials with the sinus target and two trials with the rectangular target in consecutive order. The sinus and rectangular targets had the frequency of 0.2 Hz and the peak force was set at 9 N for the children, 18 N for the young adults and 12 N for the older subjects. The peak forces were set at about 10% of the average maximal grip force in the lateral grip (about 150 N). The assessment was performed for the dominant and non-dominant hand.

The force tracking system was further used to evaluate the influence of Botulinum-Toxin treatment of spasticity on the grip force control in 38 year-old female patient. The patient suffered traumatic brain injury 8 years ago, resulting in the right-side hemiparesis. Precision grip was preserved but the patient had difficulties grasping objects due to the loss of muscle control. The patient was treated for spasticity of the wrist and finger flexor muscles with Botulinum-Toxin injection. We assessed her grip force control in the lateral grip one day before receiving the treatment and 6 and 13 weeks afterwards. In each session the patient performed three trials of the three tracking tasks (with ramp, sinus and rectangular target). The grip force control was evaluated by the average tracking error of the three trials in the sinus task. The assessment procedure was supervised by the patient's physician and the physical therapist. Written consent was obtained prior to the investigation. The study was approved by the ethics committee of Institute for Rehabilitation, Republic of Slovenia.

2.4. Training

The grip force tracking system was used as a training tool in 10 post-stroke patients (4 female, 6 male; mean age: 44.1 (SD 20.0) years). The average time between the onset of the condition and the training was about 5 months for the majority of the patients. The patients were attending regular occupational therapy program. For the training four different tracking tasks were programmed: assessment of maximal grip force, tracking of randomized ramp and rectangular signals and tracking of sinus signal with the increasing frequency. The properties of the signals were selected by the occupational therapist to maximize patient's performance during each session. Periodic signals were avoided not to reduce patient's attention span. The randomized ramp target was used to train patient's muscular control when gradually increasing or decreasing the grip force. The randomized rectangular target was mainly focused on closing and opening of the hand between different discrete force levels to enhance patient's grasp stability and hand opening. The sinus target with the increasing frequency was aimed to improve accuracy of the grip force control. The signal amplitudes included levels reaching up to 30% of the patient's maximal grip strength and the values of 0 N where the patient had to completely release the grip. The patients trained with the affected side for about 10–15 minutes daily, 4–5 times a week for four weeks. The unaffected side was tested once every five days to obtain reference results of each individual. The maximal grip force was assessed before each training session by the same device used for training. Patients either trained the grip force control in lateral grip or cylindrical grip, depending on the functional state of their affected hand. During the period of training with the grip force tracking system all patients received standard physical therapy. The training with the tracking system was supervised by the physical therapist. All the patients included in our study were informed of the procedures and gave consent to participate. The study was approved by the ethics committee of Institute for Rehabilitation, Republic of Slovenia.

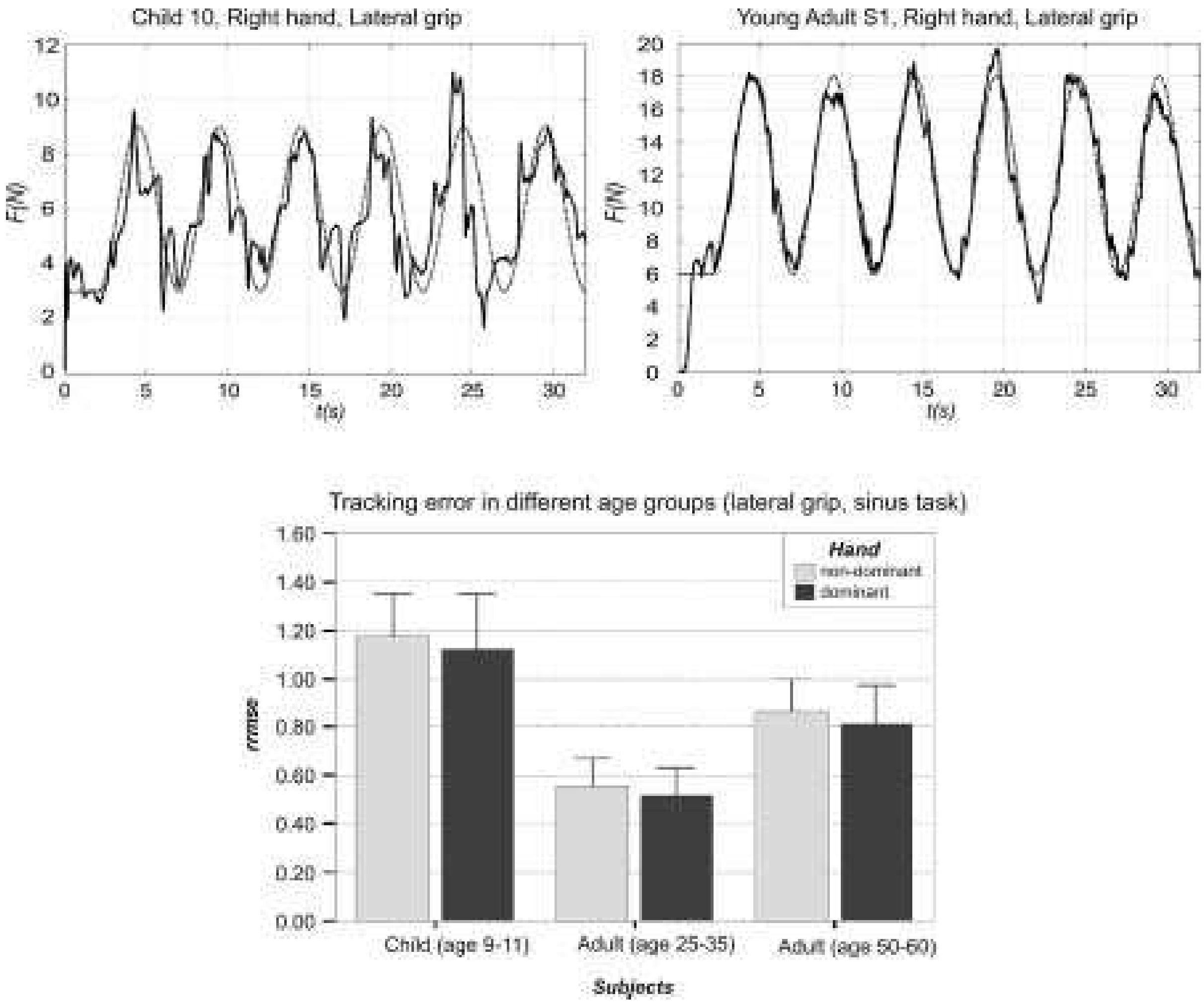

Fig. 3. Tracking results of a healthy 10-year old child and young adult (above), and the average tracking errors of three age groups of healthy subjects.

3. Results

3.1. Assessment

Figure 3 shows the results of the assessment of grip force control in three age groups of healthy subjects. Only the results of the sinus tracking are presented in the paper. The results (Fig. 3, above) show the tracking performance in a 10 year-old child and a young adult subject. The child was unable to smoothly increase and decrease the grip force which resulted in more abrupt response producing much larger tracking error (rrmse = 1.14). When the target was decreasing, the child first slightly increased the output and then decreased the grip force for a fixed force level. Results of other children show a similar approach while tracking the sinus target. The adult subject (S1) accurately tracked the target and produced a smooth response with only small deviations (rrmse = 0.48).

The performance of the tracking task was quantified by calculating the tracking error between the target signal and measured response. The bar chart in Fig. 3 (below) shows the average tracking results with standard deviation as obtained in the three age groups. The results show significant differences in the tracking accuracy among the tested groups (one-way ANOVA, non-dominant hand: $F_{2,29} = 21.268$, $p < 0.001$, dominant hand: $F_{2,29} = 13.269$, $p < 0.001$). The largest tracking error was found in the group of children, 1.173 (SD 0.282) for the non-dominant hand and 1.120 (SD 0.368) for the dominant hand. The average tracking error of the young adults was 0.552 (SD 0.165) for the non-dominant hand and 0.515 (SD 0.168) for the dominant hand. The group of older adults had the average tracking error of 0.865 (SD 0.187) for the non-dominant hand and 0.813 (SD 0.223) for the dominant hand. The lower tracking error reflects more enhanced grip force control and better hand functionality [14]. The average results of all groups show no significant influence of the hand dominancy on the grip force control.

Figure 4 shows the tracking results of a patient who suffered head injury before and after receiving Botulinum-Toxin for treatment of spasticity. Before the therapy (Fig. 4, left side), the patient was unable to gradually increase the force during the sinus tracking. The results show abrupt muscle activation patterns which resulted in non-smooth trajectory (rrmse = 1.34). The patient was overshooting the target while it was increasing. When the target force was decreasing the patient had difficulty releasing the grip which unabled her to reach the minimum peaks of the sinus. Similar pattern is also observed in the rectangular target tracking. The patient used excessive grip forces with the increasing target and was unable to regulate the output force to the desired level. The results 13 weeks after the treatment (Fig. 4, right) show that the patient was able to perform the task with much better accuracy (rrmse = 0.97). The resulting grip force trajectories are much smoother and the patient was able to increase and decrease the force within the required range. The results of the rectangular target tracking show better grip force control in patient's hand after the treatment. The patient was able to regulate the force more accurately and produced less abrupt response when the target signal was increasing. Fig. 4 (below) shows the results of the sinus tracking during the period of treatment. The results show the mean tracking error of three trials with standard deviation as obtained in each session. The patient produced considerably larger tracking errors with the affected hand as compared to the unaffected hand before receiving the treatment. After 13 weeks the patient improved her performance with the affected hand for about 30%, smaller improvements in performance were visible when the task was performed with the unaffected side. The results of the clinical tests also showed improvements in patient's hand mobility after the treatment.

3.2. Training

Figure 5 presents the result of the training with the force tracking system in 43 year-old female patient who had stroke four and a half months prior to the training. The results show patient's performance at the beginning (Fig. 5, left) and at the end (Fig. 5, right) of training for two selected tasks. Comparing the results of the rectangular target tracking shows that the patient improved the ability to control and stabilize the grip force during the constant phases of the signal. At the beginning of training the patient had difficulty keeping the grip force stable at higher force levels. After the training the accuracy of the tracking considerably improved and the output force was smoother. The results of the sinus task at the beginning of training (Fig. 5, below) show that the patient was unable to smoothly increase and decrease the grip force which resulted in more abrupt grip force response. The patient lacked the muscle capacity to track the target within the 30% of her maximal grip force resulting in large tracking error (rrmse = 1.72). After the training the patient's grip strength considerably increased and the grip force control was improved. The output of the sinus task shows a smooth response with small deviations from the target (rrmse = 0.58).

Figure 6 shows the results of the training of all patients for the maximal grip force (above) and the tracking error as assessed in the sinus task (below). The results show the average scores as obtained

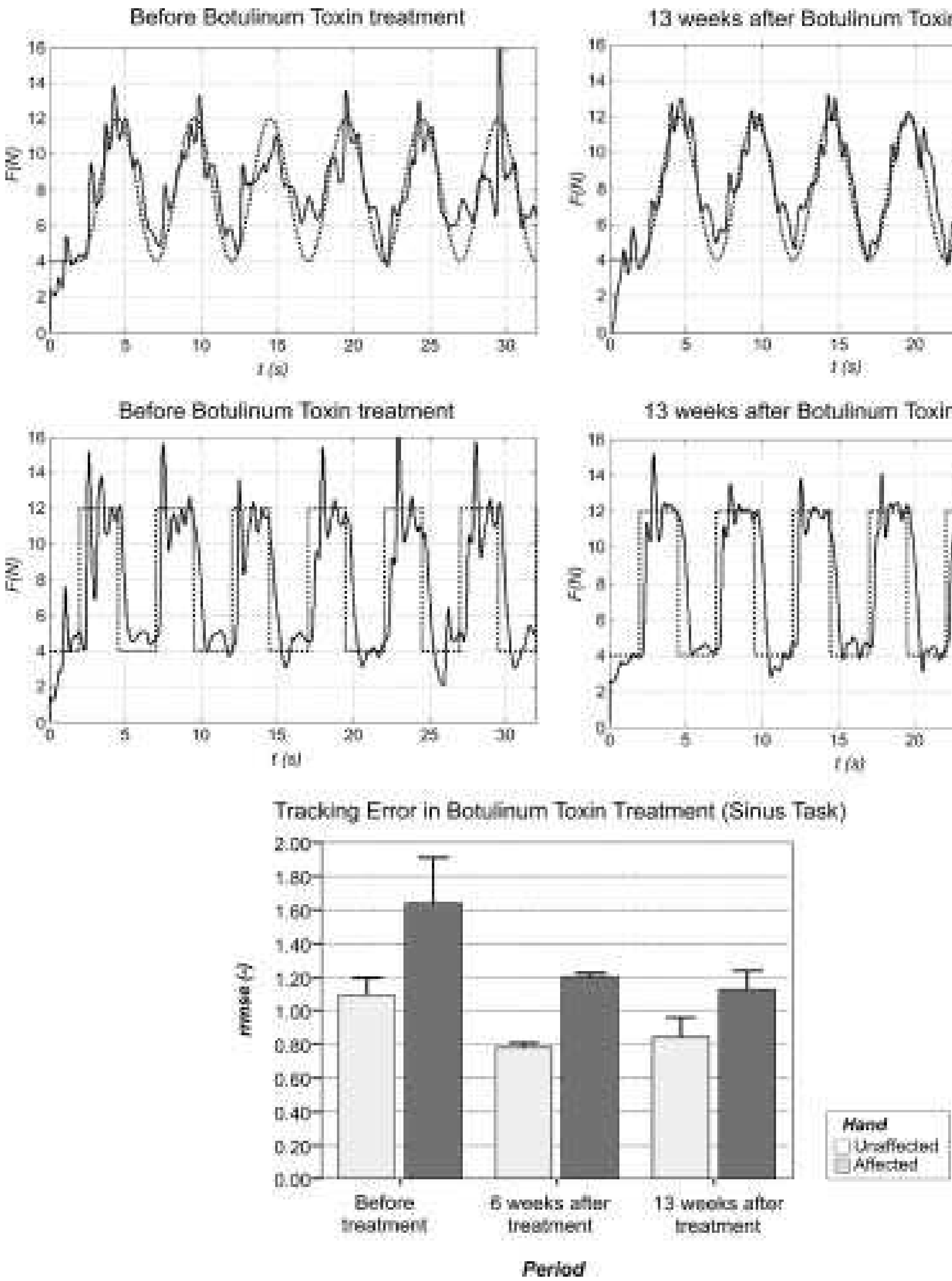

Fig. 4. Tracking results of the sinus and rectangular target tracking before and 13 weeks after the treatment with Botulinum-Toxin [5] in a patient after head injury show visible improvement of the grip force control.

during the first five and the last five training sessions. The results of the grip strength assessment show that 7 patients improved their grip strength during the rehabilitation (one-way ANOVA, $P < 0.05$). The patients P4, P8 and P10 showed no statistically significant changes in the grip strength. The percentage values in Fig. 6 indicate the amount of increase in the average maximal grip force between the first and

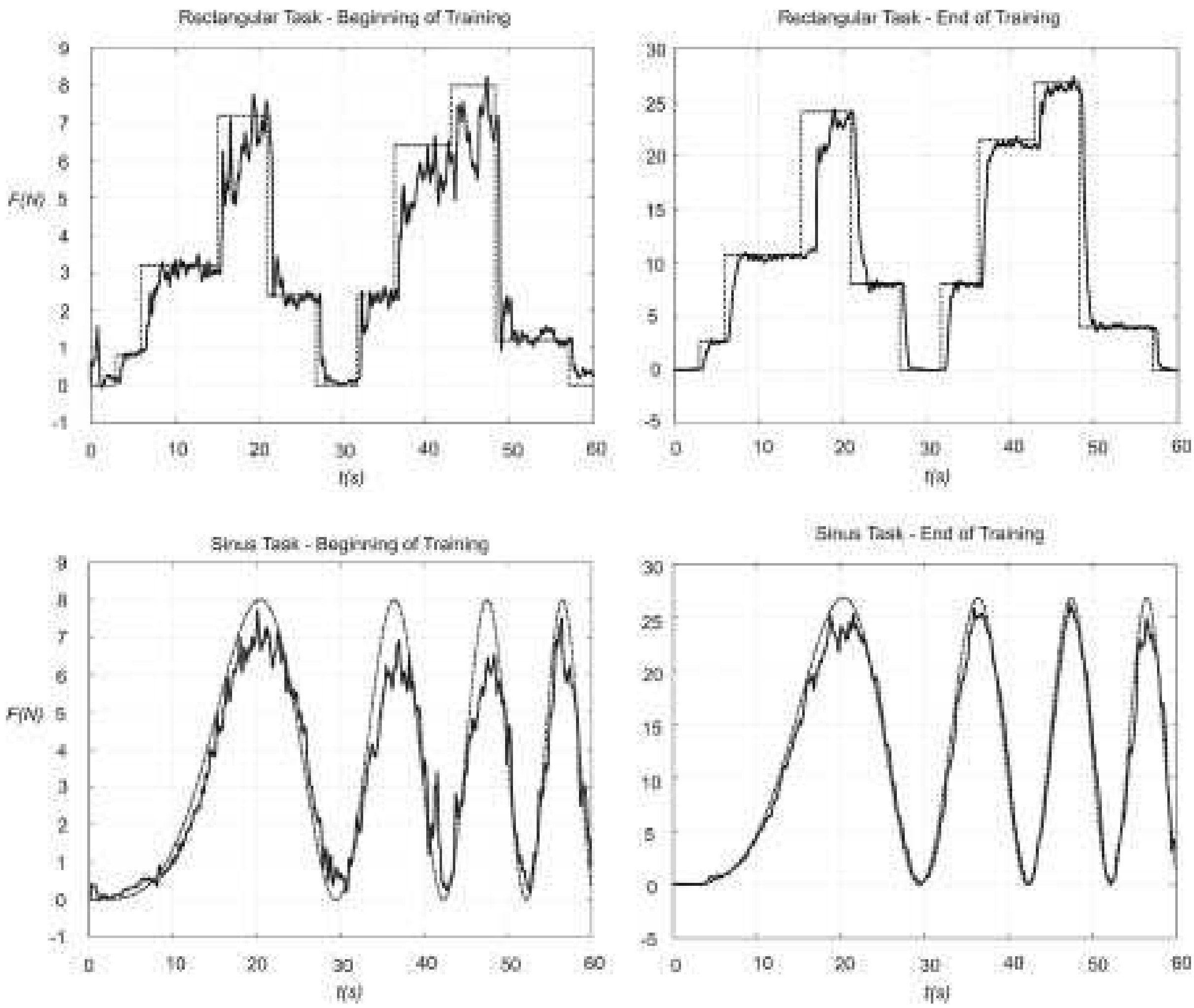

Fig. 5. The results of the tracking tasks as compared between the beginning and the end of the training period in one of the patients after stroke. The results show considerable improvements in the accuracy of the grip force control and in the release and stability of the grip after the training with the tracking system.

the last week of training. The results show large increase of the force in three patients (P5, P6, and P7) who had low grip strength at the beginning of the training. The patients who started the training with higher grip strength values demonstrated only small increase during the therapy.

The average scores of the sinus tracking task (Fig. 5, below) show that 8 patients improved their performance during the training (one-way ANOVA, $P < 0.05$). The lower tracking error suggests more enhanced grip force control [10]. The patients P8 and P10 showed no consistent results during the entire period of training. The percentage values in Fig. 6 indicate the amount of decrease of the average tracking error between the beginning and the end of training. The largest decrease of the tracking error was found in patients P5, P6, P7 and P9. The remaining patients demonstrated more advanced performance already at the beginning of training (rrmse < 1) with lesser decrease of the tracking error during the training period.

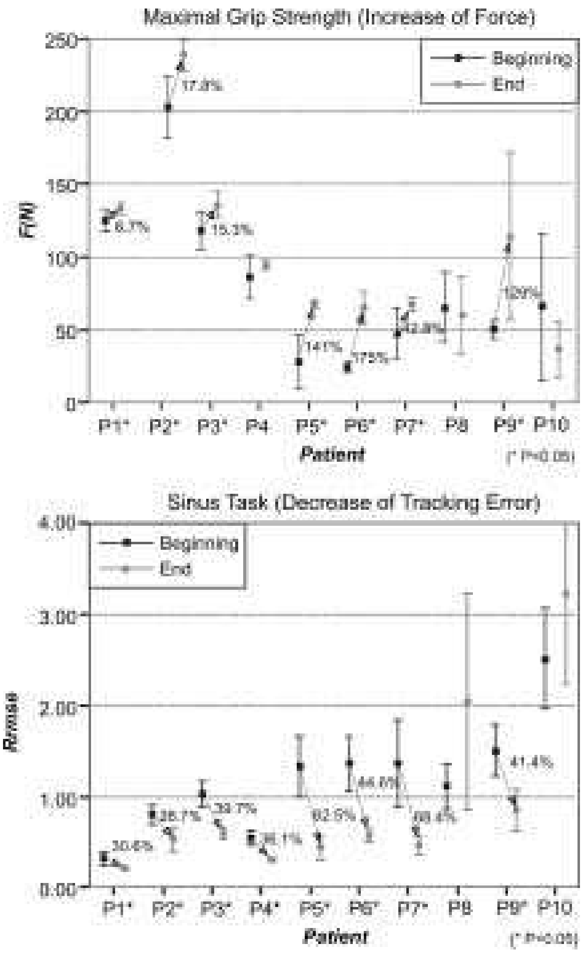

Fig. 6. The average maximal grip force and the average tracking error in the sinus task as obtained for the first and the last five sessions. The percentage values indicate the increase of the grip strength (above) and the decrease of the tracking error (below) between the beginning and the end of training. ($^{*}P < 0.05$, one-way ANOVA).

4. Discussion and conclusion

The aim of this paper was to present the grip force tracking system for the assessment and training of the grip force control. The system can assess the force with much greater accuracy as compared to the commonly used mechanical dynamometers and allows real-time computer assisted measurements of the applied force with the possibility to provide the patient and the therapist with visual feedback on the grip force. In this paper we presented preliminary results obtained in the healthy subjects and patients to demonstrate the use of the grip force tracking system as a method for the assessment and the training of hand function. Further studies with larger number of subjects are needed to more firmly support the findings presented.

We investigated the effect of age on the grip force control in lateral grip of 32 healthy subjects. The results show considerable differences in average tracking errors of the three age groups. The children produced more than twice as large errors as compared to the group of younger adults. The larger tracking error in children suggests that in this age group the grip force control in dynamic tasks is not yet as developed as in adults [1]. When tracking the dynamic targets, the children tend to precede the target signal and then correct the output by reducing or increasing the force. This strategy results in more abrupt force outputs. The analysis of the force-time curves of children shows similar findings as reported by Blank and colleagues [1], who assessed tracking of ramp target in 5-year old children. The 10-year old children in our study had no difficulty tracking the ramp target where the task required only gradual increase of the grip force (the results are not shown in this paper) however they adopted this strategy for the faster moving targets. We observed similar patterns in the group of older adults. The results show decrease of accuracy in the tracking when using the lateral grip. The older adults produced non-smooth trajectories with larger deviations during the decreasing phase as compared to the increasing phase. The results suggest that the grip force control is reduced with age. Future research should compare grip force control of dynamic targets under visual feedback in several age groups of children and adults to further investigate the changes of the grip force control with age and to evaluate the sensitivity of the tracking method.

Previous studies [6,14,22,26] have shown that the assessment of the force control under visual feedback using the tracking method may be useful for clinical evaluation. In the paper the preliminary results obtained in a patient after head-injury who was treated with Botulinum-Toxin for hand spasticity are presented. The results showed considerable differences in the force control between the unaffected and affected side before the treatment. The patient was unable to release the grip which resulted in reduced tracking performance in the sinus target. When increasing the force in the rectangular target tracking, the patient used excessive force and was unable to retain the required force level. The treatment with Botulinum-Toxin and the physical therapy, the patient received during this period, improved her ability to control the muscles of the affected hand. The patient was able to release and control the grip with much greater accuracy. Due to the effects of the treatment with Botulinum-Toxin [3] the patient's muscular strength decreased. The patient's hand function was clinically assessed only by means of Canadian Occupational Performance Measure (COPM) which is mainly focused on the evaluation of the functional movement tasks of the entire arm thus providing less information on hand function and the control of force. The tasks included in COPM that require accurate force control of the hand are writing and feeding tasks [17]. The patient showed improvement in writing (before: 4, after: 7) and feeding (before: 2, after: 8) with the affected hand after the therapy. Further study is needed to investigate the sensitivity of the tracking method to validate the effects of Botulinum-Toxin treatment on the grip force control and find parallels between the tracking results and the clinical tests used in occupational therapy and rehabilitation.

To investigate the effects of the isometric training of the hand function, the proposed tracking system was applied as a training method for 10 patients after stroke. Four different computer tasks were aimed to assess the maximal grip strength and to possibly improve the accuracy of the grip force control while enhancing the ability to balance and release the grip. During training the difficulty of the tracking tasks was increased by raising the maximal level of the target force to maximize patient's performance in each session. Seven patients improved their maximal grip strength and the grip force control during the training period. The analysis of the force time curves showed that the highest reduction of the error between the beginning and the end of training occurred in the sinus task which was described as the most difficult task by most of the patients. In the sinus task 8 out of 10 patients improved the overall accuracy of tracking and consequently achieved better grip force control. Two of the patients (P8 and P10) showed no consistent results of the training with their tracking scores fluctuating between sessions. The patient P8 experienced the last stroke 6 years prior to the testing and also showed no observable improvements in other methods of therapy. The patient P10 was the oldest patient in the group (age

79) which could be a possible factor for a slow progress during the rehabilitation. The patients who were unable to reach the 30% level of their maximal grip strength at the beginning of training improved their performance considerably and were able to reach the highest target levels in the last few training sessions. The patients trained with the grip force tracking system over the period of four weeks in combination with the standard physical therapy. Each training session lasted only about 15 minutes per day to minimize fatigue. The tracking tasks were very positively accepted by the patients as well as by the therapists.

The assessment of the grip force control is important for the evaluation of hand function in patients after central nervous system injury [6,14], patients affected by neuromuscular diseases [16] or Parkinson's disease [24] and persons after hand injury [6]. The proposed tracking method could be efficient in connection with different rehabilitation therapies (e.g. physiotherapy, functional electrical stimulation, drug treatment) to follow the influence of the therapy on patient's muscular strength and grip force control. The biofeedback associated with the performance of the tracking task can further assist the overall rehabilitation process by providing feedback on the progress to the patient [4,21]. The advantage of the tracking method is also in the objective measure provided as a result of training which could be used to accurately evaluate the progress of therapy. The difficulty of the tasks can be adjusted to patient's maximal abilities to advance the performance during the training. The therapy with the biofeedback on the grip force could enhance the process of relearning the sensory-motor functions after central nervous system injury as other studies suggest [14,26]. With visually more attractive feedback (e.g. in a form of a computer game) the system could be especially appropriate for training of young children and adults with sensory-motor impairments.

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