FACULTY OF MEDICINE AND HEALTH SCIENCES

MOVEMENT ANALYSIS OF THE UPPER LIMB IN CHILDREN WITH UNILATERAL CEREBRAL PALSY: FOREARM PRO- AND SUPINATION.

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Preface

We enjoyed working in the paediatric orthopaedics department of the University Hospital of Ghent, where we have spent numerous hours figuring out marker placements, protocol exercises, parameters and so on. We could not have done this without the help of several important people, who we would like to thank in this part of our scription.

When we faced problems of any nature, we could always count on Ellen Dedobbelaere. She was always there to answer all our questions and to provide us with tips and tricks on how to work our way in and around the lab.

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We would like to thank prof. dr. Plasschaert, the promotor of this thesis, for giving us the opportunity to work on this project. We have learned a lot by being able to develop the protocol by ourselves and having the opportunity and the freedom to think of our own exercises. We were allowed to use the resources of the Cerebral Palsy Reference Centre and the gait analysis lab.

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Table of content

Abstract

INTRODUCTION Cerebral Palsy (CP) is a non-progressive neurological disorder often leading to motor impairments. It is caused by damage to the brain in the early stages of its development, this is before, during or after birth. The upper limb is involved in 60% of the children with CP, leading to difficulties in handling objects and independence in daily life activities. There are numerous classification systems for scoring the upper limb function. However none of these are objective. Therefore this study focusses on developing an objective movement analysis with the aid of kinematic and EMG registrations. Because the upper limb is very complex regarding its degrees of freedom in which movement is possible, it is chosen to only focus on the pro- and supination.

METHOD This study is designed to assess the difficulties encountered during pro- and supination objectively incorporating kinematics and EMG data. 12 Patients and 12 age- and gender matched controls are evaluated in the gait analysis lab of the University Hospital of Ghent. To create the kinematic axissystems and graphs, retroreflective markers are placed on the subject's arms. EMG electrodes are placed on the Pronator Teres muscle and the Biceps Brachii, to retrieve information about muscle activity. After this the subjects perform analytical as well as functional tasks as instructed. With the help of parameters selected for each exercise, data on the pro- and supination performance is gathered.

RESULTS Due to the limited timeframe the data of only one patient with a rather severe form of CP and its control are compared. The clinical assessment of the patient describes a nearly impossible active supination. These findings are confirmed by the results of the protocol. It is clear that the patient's affected arm had an inferior performance for almost all parameters compared to its control and to his own dominant hand.

DISCUSSION There are a few points of discussion concerning the protocol, its execution and the results. However, these points are not insurmountable and can be easily adjusted in the future. Key is that the kinematic model is capable of assessing the pro- and supination rotation in an objective and quantifiable way.

CONCLUSION By creating an objective assessment of the upper limb and describing its pro- and supination function on a rather small scale, it is hoped that clinical and therapeutic decision making will be possible using this protocol. Future studies should concentrate on proving the protocol’s value in the everyday practice.

Nederlandstalige samenvatting

Deze thesis handelt over onderzoek naar de bovenste lidmaat functie van kinderen met een cerebraal parese, meer bepaald naar hun pro- en supinatie capaciteiten. Cerebraal parese is een niet-progressieve neurologische aandoening die veroorzaakt wordt door hersenschade die opgelopen werd tijdens de ontwikkeling van de hersenen. Dit kan voor, tijdens of na de geboorte zijn. Deze schade heeft belangrijke implicaties op het functioneren van de patiënt, voornamelijk door motorische moeilijkheden. De prevalentie bedraagt 1-2 op duizend levendgeborenen. Het bovenste lidmaat is bij 60% van de kinderen betrokken, wat belangrijke beperkingen in het uitvoeren van activiteiten in het dagelijks leven met zich meebrengt.

Er zijn 4 verschillende CP subtypes: spastisch, dyskinetisch, ataxisch en gemengd. De subtypes worden bepaald op basis van de klinische neurologische presentatie, die afhankelijk is van de plaats en het tijdstip van het hersenletsel. Het spastische subtype is het meest voorkomende (80%). Door de grote variabiliteit in het tijdstip van het optreden van het letsel en in klinische presentaties ervan, is steeds een persoonlijke behandeling nodig voor elke patiënt. De aanpak is bovendien multifunctioneel en langdurig, waarbij voornamelijk nieuwe complicaties worden voorkomen en de beperkingen op het functioneren aangepakt worden.

Er bestaan verschillende classificatiesystemen om de bovenste lidmaatfunctie van patiënten te scoren, al deze systemen zijn echter subjectief en berusten louter op de beoordeling van de ouders of een therapeut. Verschillende onderzoeken kaarten aan dat het nodig is om een objectieve test te ontwerpen die de therapiekeuze kan begeleiden en duidelijk verschil kan aantonen voor en na therapie. Het implementeren van een kinematische analyse en de registratie van spieractivatie met behulp van elektromyografie (EMG) zou zo'n analyse objectiever kunnen maken.

In deze studie werd een protocol ontworpen die aan deze objectieve eisen zou kunnen voldoen. Zo werd de pro- en supinatie vergeleken tussen 12 normaal ontwikkelende kinderen en 12 kinderen met unilaterale cerebraal parese. Alle kinderen waren tussen 6 en 14j jaar en werden aan elkaar gekoppeld op basis van leeftijd en geslacht. De studie vond plaats in het ganglabo van het UZ Gent. Dit labo beschikt over 24 3D camera's en 4 videocamera's die aan de hand van retroreflectieve markers de beweging van de testpersoon kunnen volgen. De plaatsing van deze markers werd nauwkeurig uitgewerkt zodat optimale tracking en resultaten konden bereikt worden. De EMG elektrodes werden geplaatst op de musculus Pronator Teres en musculus Biceps Brachii. Dit alles op beide armen van de testpersonen.

Het protocol dat werd ontworpen bestond uit twee delen. Een eerste deel bestond uit een set van analytische opnames. Hierbij werd de testpersoon, zittend en met de ellebogen ondersteund, gevraagd om pro- en supinatie cycli uit te voeren. Dit werd zowel bimanueel als

voor elke arm apart gedaan. Het tweede deel bestond uit 3 functionele oefeningen. Elk van deze 3 oefeningen werd met een apart doel ontwikkeld. Zo werd een oefening met een pingpong racket ontworpen die de focus legde op snelheid en het vasthouden van een object. Een volgende oefening waarbij de testpersoon gevraagd werd een marker op het hoofd te bedekken, liet toe om snel een inschatting van de ernst van de beperking op het dagelijks functioneren te maken. Tot slot een bimanuele oefening waarbij de persoon gevraagd werd te klappen op de middellijn die kon aantonen dat de dominante hand de mindere prestatie van de andere hand kan compenseren.

Voor deze oefeningen werden verschillende toepasbare parameters gekozen. Zo werd steeds de gemiddelde bewegingsboog bepaald alsook de maximale pro-en supinatie graden. Verder werd er naar de snelheid, versnelling en vlotheid van beweging gekeken voor de analytische oefeningen. Bij de pingpong oefening werden alle parameters overgenomen behalve degene voor vlotheid. Voor de oefening waarbij het hoofd wordt aangeraakt werd naast de bewegingsboog ook naar het succesvol uitvoeren van de oefening gekeken. De klapoefening werd besproken aan de hand van de afstand tot de middellijn van beide handen op het moment van de klap. Voor al deze parameters werden de resultaten vergeleken tussen de patiënt en zijn controle voor dominante handen en niet-dominante handen. Ook binnen de proefpersonen zelf, werd links met rechts vergeleken.

Al deze zaken werden toegepast op één patiënt met een ernstige vorm van CP en zijn controle. Hier werden volgende zaken opgemerkt. De bewegingsboog was duidelijk veel beperkter aan de aangetaste zijde van de patiënt in vergelijking met zijn andere zijde en met de niet-dominante zijde van zijn controle. Deze boog werd voornamelijk beperkt door het onvermogen een supinatie uit te voeren. Ook de snelheid en acceleratie gaven een sterke beperking weer. De vlotheid was duidelijk beperkter voor de aangetaste zijde. Wanneer de unimanuele oefening werd vergeleken met de bimanuele viel het op dat de dominante zijde van de patiënt over het algemeen beter scoorde tijdens de unimanuele oefeningen. In de klapoefening werd duidelijk aangetoond dat de beperkte rotatie van de aangetaste kant werd gecompenseerd door een grotere supinatieboog aan de dominante zijde.

Het ontworpen protocol en zijn bijhorend kinematisch model hebben aangetoond in staat te zijn op een objectieve en kwantitatieve manier de beperkingen van patiënten met CP vast te stellen. In de toekomst is het belangrijk te bewijzen dat dit protocol ook klinische relevant is. Therapeutische beslissingen moeten kunnen gemaakt worden op basis van informatie verzameld uit dit onderzoek.

Introduction

What is Cerebral Palsy?

Cerebral palsy (CP) is caused by damage to the developing brain during fetal development or during the first years of life (1–11). The result of this damage is a non-progressive neurological disorder with motor impairments, called cerebral palsy (1–5,8–11). The damage can be due to maternal infections like rubella, chorioamnionitis and cytomegalovirus or pre-eclampsia (5,6,10). Other risk factors for the acquisition of brain damage are low weight or hypoxic events at birth, multiple pregnancy, premature birth, neonatal seizures, infection, restricted intrauterine growth, vascular incidents and placental abnormalities (4–6,10). In 10% of the cerebral palsy patients, damage to the developing brain occurred in the postneonatal period, with infections of the central nervous system, seizures and (non-)accidental head trauma as potential causes (6). However this subgroup is often excluded from trials investigating risk factors during pregnancy and birth (4).

As a consequence of the brain lesion, movement and posture of these children can be disturbed, caused by one or several of the following symptoms: spasticity, loss of selective motor control, co-contractions, muscle weakness, hypertonia and hyperreflexia, mirror movements and decreased velocity of movements (2,8,11–13). In addition they often display sensory deficits, cognitive impairments and problems with communicative and social skills, together with secondary musculoskeletal problems and epilepsy (2,5,7,12). The secondary musculoskeletal problems are caused by hypertonia and weakness of the involved muscles, leading to muscle contractures. The muscle imbalance in combination with skeletal growth causes bony deformities (2,8).

CP is a descriptive term that covers the largest group of movement disorders in children (2,4,5,7,10,14). It is not a diagnosis, as the term covers nothing about the location, type or timing of the injury (4). Out of 1000 live births, 1 to 2 children are born with CP (2,5,6,10,14,15). In children born before 28 weeks gestational age the prevalence of CP even increases to 40-100 per 1000 (2,14). These premature babies have a higher risk of intraparenchymal or intraventricular bleeding and damage to the periventricular white matter, which could harm the developing brain (5).

Neuroplasticity

The developing brain is most vulnerable in the most rapid phase of its growth, which is from in utero until approximately 5 months after birth (2). In this stage, infection, malformation or disruption of the blood supply can damage the brain (2). In the first 3 months of development, the blood supply originates from the front and the back of the brain and stretches out to the more central and deeper structures. These structures in the periventricular zone of the motor

cortex are far away from the developing blood vessels and thus more susceptible to be damaged by disruption of the developing blood supply (2). However, at full term, the most vulnerable cells in the brain are the basal ganglia. These are the cells with the highest metabolic needs and are thus compromised in a hypoxic situation in the perinatal stage (2).

The various possible stages of development of the central nervous system at the time of the injury and different possible locations of the brain lesion lead to different clinical presentations and have a harmful effect on the functional capacities of the child (2,6,12,16,17). The ability of the brain to compensate for this injury, depends on its developmental stage at the time of the insult (14,16). The developing brain has a greater reorganizing capacity than the adult brain because it can react by taking over the affected brain functions in different, atypical locations (16,18).

Approximately 20 weeks post conception, the corticospinal axons of the motor cortex of both hemispheres have reached the cervical spinal cord, where they connect mainly with alfa-motoneurons (16). Because of the bilateral projections of both hemispheres at this stage of the development, competition between the ipsilateral and contralateral projections to the extremities occurs (16). This means that the extremities receive motor signals from both the ipsilateral and contralateral hemisphere (16,18). Neuronal activity during the third trimester and the first years of life in normal brain development then leads to the disintegration of the ipsilateral projections and the consolidation of the contralateral projections to the extremities (16). The ipsilateral innervation of the extremities is thus transient (14,16). A lesion that occurred during the early developmental stages of the brain, resulting in less neuronal activity coming from one hemisphere, leads to the persistence of the ipsilateral projections from the contralesional hemisphere to the extremities because of its dominant neuronal activity during the competition (16). This process is called neuroplasticity or reorganization and is responsible for the innervation of the paretic extremities (14,16). However, normal function of the paretic limb has not yet been reported with only ipsilateral projections (16).

Because the contralesional hemisphere now innervates both the ipsilateral and contralateral extremities, mirror movements can persist. Mirror movements are symmetrical movements of the contralateral limb and are a normal phenomenon in typically developing children until 8 years old. It starts to disappear by the age of 9 and should be gone at 12. By this age, all ipsilateral projections should have disintegrated as a result of the dominant neuronal activity coming from the contralateral hemisphere (19). Due to damage to the developing brain, both the ipsilateral and contralateral projections of the contralesional hemisphere persist in children with unilateral CP, leading to the occurrence of mirror movements (19).

Cerebral palsy subtypes

There are four subtypes of CP according to the Surveillance of Cerebral Palsy in Europe (SCPE): spastic CP, dyskinetic CP, ataxic CP and mixed or unclassified CP (9,10,15,17). These subtypes are based on the clinical features and clear neurological signs (9). Only when the patient reaches the minimum age of 4 or 5, the diagnosis of CP can be confirmed as progressive neurological diseases or other causes of motor impairment will have become apparent by then (4,9,14,17).

Spastic CP is by far the most common subtype, diagnosed in more than 80% of the CP patients (7,14,20). Damage to the motor cortex of the brain affects the corticospinal or pyramidal system, which is responsible for organising goal oriented, complicated movements. An injury to this system can induce spasticity, hypertonia, abnormal patterns of movement and/or posture as well as hyperreflexia in the contralesional side of the body (5,9,10,21). Damage to the cortex can also lead to focal epilepsy (9,21).

The increased muscle tone is explained by the inhibition of the release of γ-aminobutyric acid (GABA). The release of this inhibiting neurotransmitter is normally stimulated by the descending corticospinal tracts and leads to the interruption of reflex arcs (2). A lesion of the corticospinal tracts, as occurs in spastic CP, prevents the release of GABA and thus prevents the interruption of these reflex arcs (2). The muscles become overactivated and show an increase in tonic stretch reflexes, called spasticity, which are velocity dependent (2,7,9). Young children often display spasticity, which is dynamic and mostly interferes with function. Non-surgical interventions can be used to reduce spasticity while older children might have developed more fixed contractions, which require surgery (7).

The prevalence of dyskinetic CP is approximately 6.5%. The symptoms of this CP subtype, as defined by SCPE, are loss of coordination, disturbed posture and abnormal movement patterns. Movements are often uncontrolled and involuntary and they can be provoked by a sensory overload such as anxiety or noise (2,5,9,10,21). This CP subtype can be subdivided into dystonic and choreo-athetotic CP, in which the latter consists of hyperkinesia with hypotonia and the first is typed by hypokinesia and hypertonia (9,10). These symptoms can be explained by a lesion to the extrapyramidal system, consisting of the basal ganglia (2,21).

The basal ganglia are responsible for the coordination of reflex patterns. This leads to fast and smooth movements, which are adjusted by visual and proprioceptive input. Damaging this complex interaction of motor control can affect the fluidity of movement and lead to this subtype of CP (2).

Patients who are categorized in the ataxia group have most difficulties coordinating movements, displaying an abnormal rhythm, force and accuracy (2,9,10). These symptoms

can be explained by lesions in the cerebellum, which role is to coordinate movements that are initiated by the corticospinal system (2,21). Hypotonia and intention tremor can also be observed in this subtype (9). The prevalence is approximately 4% (20).

When the characteristics of more than one subtype are seen, classifications are made based on the most dominant movement pattern or clinical feature (9). Classifications can also be made into bilateral or unilateral CP, based on the distribution of the limb involvement. Bilateral CP indicates involvement of the limbs of both sides of the body, while only one side of the body is affected in unilateral CP. In unilateral CP, the involvement of the upper limb is often more severe than the involvement of the lower limb. On the contrary in bilateral CP, the involvement of the lower limbs is most severe (9,17). Bilateral spastic CP is the most common CP subtype (10,20). Other possible classifications are based on the timing (prenatal, during birth or postnatal) or the location (pyramidal, extrapyramidal, cerebellum, cerebral cortex) of the injury (5,6).

Upper limb involvement in cerebral palsy

In 60% of CP patients, the upper limb is involved resulting in a compromised bimanual function as demonstrated by the MACS *(see infra)* (1,3,11,17,22,23). The combination of an internal rotation contracture of the shoulder, a flexion contracture of the elbow and flexion-pronation contracture at the wrist with ulnar deviation is frequently seen in the upper limb (1,2,7,15,24). Next to these, a thumb in palm deformity, in which the thumb abduction is insufficient, and a swan neck deformity, with hyperextension of the proximal interphalangeal joints and flexion of the distal interphalangeal joints, can be seen (7,15). In addition, studies comparing unilateral CP patients to typically developing children show longer movement durations, reduced speed and smoothness of movements in combination with increased trunk anteflexion (24).

These contractures and aberrant movement patterns have great impact on the patients' functional abilities and their independence in daily life activities, as they interfere with accurate positioning of the hand, grip, reaching, release and bimanual coordination (1–3,7,11,13,15,22,24,25). Adequate function of the upper extremity is also important for communication, hygiene and social contact (15,17). In addition, especially older patients, might worry about the appearance of the hand (7,15).

The effect of both muscle weakness and spasticity, leading to an imbalance between agonist and antagonist muscles is for example seen in the forearm where the Biceps Brachii muscle is a supination agonist and the Pronator Teres muscle is a pronation agonist. In the forearm, the Supinator muscle and the Biceps Brachii (BB) muscle are often weak, while the Pronator Teres (PT) and Quadratus (PQ) muscles are often spastic, leading to a pronation contracture in the forearm (1,7). Because of this, the BB becomes overactivated in functional tasks, when

both supination of the forearm and extension of the elbow are required, to conquer the spasticity of the PT and PQ. This overactivation will subsequently lead to a flexion contracture and less supination in the elbow (1). The pronator spasticity, the difficult active supination and the possible secondary flexion contracture obviously have a great impact on the children's functional abilities and performance in daily life activities and should therefore be prevented, detected and addressed by regular follow-up and treatment when necessary. The focus of this study is on objectively describing pro- and supination in children with cerebral palsy, in order to focus therapy, improve function in daily life activities and integration into society.

Interventions

The follow-up and treatment of children with CP requires a multidisciplinary approach and involves paediatricians, physiotherapists, social workers, orthopaedic surgeons, neurologists, teachers and so on (2,5–7). They work together to limit the impact of the brain lesion, the physical impairment and secondary deformities on the daily life activities and well-being of the child (2,8). The goal of the multidisciplinary approach is to improve participation and function of the child by strengthening weakened antagonist muscles, reducing spasticity of the agonist muscles and by prevention and correction of secondary deformities (2,6–8). Systematic and regular re-assessment is important, to evaluate the impact of interventions and for the early detection of secondary deformities (2).

The physiotherapist and the occupational therapist work together to improve the patient's functional motor abilities and play a central role in the treatment of the CP patient (7,8). The type of intervention used and the activities that are trained differ per child, taking into account their age, cognitive abilities, treatment goals and the type and severity of the motor impairment. To maximise treatment effects, the techniques and strategies that are learned in therapy must be applied at home and in school as well (7). The physiotherapist mostly works on gross motor skills and aims to improve mobility of children with cerebral palsy, while the focus of the occupational therapist is more on fine motor skills with a task specific approach. Children in physiotherapy practice sitting, standing, walking and displacements with the help of a wheelchair, orthoses or other tools (8).

One of the approaches applied for the treatment of learned non-use is constraint induced movement therapy (CIMT) (7,8). The phenomenon of learned non-use is frequently seen in unilateral CP, when the child has learned to complete bimanual tasks mainly using the unaffected arm and hand. This non-use also aggravates the muscle weakness in the affected arm (7). In CIMT, the unaffected or least affected arm is restricted during several periods per day so children are obligated to use their affected arm to complete tasks (7,8). Furthermore

the weakened muscles are trained during progressive resisted exercises, spastic muscles are stretched and the joints are passively mobilised (7)

Other approaches in physio- and occupational therapy are the cognitive approach, in which the several movement components that are part of difficult functional tasks are practised, in order to become skilled in these tasks with a focus on optimal functionality instead of good quality (7). In neurodevelopmental therapy the desired movements are guided by the occupational therapist. By stretching and traction, pathological movement patterns are inhibited while mature and more functional movement patterns are promoted (7,8). This approach is based on the process of neuroplasticity (8). Physio- and occupational therapy are an essential part of the management of the CP patient (7).

In addition to physical and occupational therapy, splints and orthoses are used to reduce and prevent muscle contracture caused by spasticity and to improve function (7,8,23). By their external application, they support the weakened musculoskeletal system of the patient, not only of the upper limb. Some splints are mostly worn overnight, because they interfere with upper limb and hand function. Their main goals are to prevent and reduce muscle contractures, to inhibit high muscle tone or to stretch and lengthen specific muscles but attention must be paid to the effect of immobilization on muscle atrophy. Other splints can be worn during specific daily life tasks, as they provide an optimal positioning of the hand, the thumb and the upper limb (7,8,23). This use of splints is part of the activity and participation-centred approach of CP and enhance the patient's independence (23).

Next to this, the neurotoxin botulinum toxin A can be used to reduce local spasticity when no fixed deformities are present (2,7). The goal of reducing spasticity is to reduce the risk of developing muscle contractures and secondary bony deformities (7,8). Guided by electromyography (EMG) or ultrasound, the intramuscular injection of this neurotoxin induces an irreversible block of the release of acetylcholine at the neuromuscular junction and thus leads to temporary muscle relaxation (2,6–8). Because of the subsequent synaptic regression, and in combination with splints and intensive physical therapy, this relaxation lasts approximately 3 to 5 months. In this period, an improvement of function, range of motion and a reduction of spasticity is seen (2,7,8). This strategy to attack spasticity is frequently used in the PT, the Flexor Carpi Radialis and Ulnaris muscles, the BB and the Brachialis muscle. Adverse effects following the injection can be pain and bruising at the site of injection and possible grip weakness which resolves within 3 months (7).

The aim of surgery in the upper limb is to improve range of motion, function and appearance and to release contractures of spastic muscles, but it can never induce normal upper limb function. One of the strategies used is tendon transfer, where for example the Flexor Carpi

Ulnaris is transferred to the Extensor Carpi Radialis Brevis to improve wrist function while it also slightly improves forearm pronation. Rotational deficits of the forearm or the upper arm can be corrected by an osteotomy, but this not a frequent intervention. Other possible procedures are the releases or the lengthening of tight structures such as the BB, the bicipital aponeurosis, the PT or the Brachioradialis muscle. When possible, surgical interventions are postponed until the patient reaches skeletal maturity as growth could induce the recurrence of the corrected deformity. Pending surgical treatment, conservative measures such as splinting can be used. Careful selection of patients who could benefit from these interventions is important, as the upper limb function of many CP patients will not improve by surgical interventions. Of all subtypes, the best surgical results are obtained in spastic CP (7).

Classification of the functional ability of the upper extremity

Because of the disturbed movement patterns, CP can affect functional tasks and integration into society (1–3,5,6,11,15). To describe the functional ability of the hand, which can change over time, different classification systems such as the Manual Ability Classification System, the Gross Motor Functional Classification system, the House Scale, the Jebsen-Taylor Hand Function Test, the Melbourne Assessment of unilateral Upper Limb Function and the Assisting Hand Assessment are often used.

The Manual Ability Classification System (MACS) categorizes the ability of the arm and hand to handle objects in daily activities into five levels, based on the child's overall daily performance (2,13,15,17,19,26). Level 1 is the highest score and means the child is completely independent in handling objects manually. When the child is fully dependent in handling objects, hand function is at level 5. It is scored by an assessor while observing the child or by someone who knows the child well (2,13,15,17,26). The MACS focusses on bimanual capacities, with no specific focus on one hand. Many unilateral CP patients have learnt to compensate for the lack of gross and fine motor skills in the impaired upper limb and are able to perform daily life activities without using both hands, resulting in a MACS score of 1 or 2 (2,13,15,17). The Gross Motor Functional Classification System or GMFCS is the equivalent of the MACS and scores the mobility levels of the patient. It divides patients into 5 groups based on their level of mobility. Level 5 are children who are completely dependent for mobilization and level 1 children who are completely independent for mobilization (2,15,19).

For the performance of the affected hand in bimanual tasks, the Assisting Hand Assessment (AHA) is developed for children between 18 months and 12 years of age with congenital unilateral impairment of the upper limb (13,19,27). It involves a video recorded session in which the children participate in a play session or a board game, according to their age. It is guided by a therapist and the session is scored afterwards using the video recording. The performance

of the assisting hand receives a score between 1 and 4 on 22 components of hand use such as pace of movement, general use, coordination and fine motor skills. The maximum score of 88 points means the impaired upper limb is used as a typically developed non-dominant hand while the minimum score of 22 points means the assisting hand is not used at all (13,26,27).

The spontaneous use of the affected upper extremity is scored between 0 and 8 by the House Scale (7,26). It is designed for children between 2 and 20 years old and relies on observation of the patient. There are no specific tasks to be executed and no time requirements. The spontaneous use is scored as absent (grade 0), passive or active (grade 8). The Modified House Classification (MHC) describes 32 additional points (26).

Starting from the age of 5, patients can be scored on the Jebsen-Taylor Hand Function Test. This test measures the effective use of the hand in daily life activities. Both the dominant and non-dominant hand have to complete 7 timed subtests. (Sub)total scores can be compared to data retrieved from a reference population with the same age and gender or to the subject's previous performances, to measure change in effective use. Completion of the Jebsen-Taylor Hand Function test takes 15 to 30 minutes. However, its reliability and validity to detect change is controversial (26).

To describe unilateral limb movements in CP patients or children with neurological impairment, the Melbourne Assessment of unilateral Upper Limb Function (MUUL) is used. For children between 5 to 15 years old, this test can describe unilateral upper limb movements and its characteristics like active range of motion, fluency and accuracy on a 122 point-scale (7,19,26). It scores 16 items based on the video evaluation of several performed activities. Both the implementation and the scoring afterwards take 30 minutes. The obtained score is then converted into a percentage. Greater quality of the upper limb movement gives a higher percentage score (19,26).

The existing classification systems to score the upper limb function in children with CP are numerous. Although these scales are already defined, validated and standardized, they have a highly subjective component and do not incorporate EMG or kinematic data. They rely on the observer who visually scores the test or on the patient and the parents who fulfill the questionnaires (11,28). In these tools, quality of movement is often scored with ordinal ratings (25). Another point of discussion is their sensitivity and ability to detect meaningful improvement of function after intervention (11,25). Furthermore these tools tend to score the patient's capacities in a test situation, while therapeutic interventions focus on what the child really does in order to improve their level of participation (3,19,27). Therefore the use of these classification systems in combination with other more objective measures such as 3D movement analysis and EMG is necessary (25,28). This combination could tell more about

pathological upper limb movement strategies, which makes it possible to direct the treatment to the patient's functional needs (1,25).

Kinematics in the evaluation of the upper limb

To make upper limb movement analysis repeatable and comparable to one another, a standard set of guidelines must be defined. These would enable the generation of a normative data set which can then be used as a reference (29,30). The guidelines must incorporate EMG data and 3D analysis of movement, consisting of a selection of relevant tasks and an accurate biomechanical model (25,31). By objectively quantifying the patient's motor performances and establishing a functional pathological profile of the patient, kinematic evaluation could support the decision making process in treatment of CP patients (24,31). Early and adequate treatment planning is essential to improve the arm and hand function of patients and thus their independence in life. The kinematic study, including both spatiotemporal and kinematic parameters, in combination with EMG registration potentially offers quantitative objective information about (pathological) motor strategies associated with specific tasks (24,28).

In the lower limb, gait analysis is used to support the clinician in treatment planning and to monitor intervention outcomes (25,29,30). Normal gait is a well described, cyclic and repeatable motion with little interindividual differences which makes it possible to define a normal, reference gait pattern (29,30). Parameters extracted from the gait analysis are, among other things, the number of steps per unit of time, the distance covered per unit of time, step length and step width (30). Joint angles can be calculated from the retroreflective markers applied to the lower limb and combining this information with the ground reaction forces measured by forceplates, makes the description of kinetic parameters in the lower limb possible. All of these parameters enable the clinician to detect and describe an abnormal gait pattern, so therapy can be adjusted to the patient's needs (30).

The various possible movements in the upper limb, their complexity and the greater range of motion make the interpretation of its kinematic evaluation more challenging than it is in the lower limb (29,30). The cyclic, repetitive and reproducible movement patterns seen in gait, are absent in the upper limb (29,30). The greater range of motion of the upper limb introduces a bigger problem of skin and soft tissue movement and the multiple degrees of freedom lead to different possible ways to perform a certain movement (29,30). In contrast to the lower limb, wide rotations around longitudinal segmental axes are seen in the upper limb, which is an additional obstacle in the interpretation of its three dimensional movement analysis (30). Most of the range of motion of the lower limb movements occurs in the sagittal plane which allows a good approximation with a two dimensional approach. This is not the case for the upper limb, where the movements cannot be described in 2D (30). The force plates used in gait analysis

to calculate joint moments and joint forces, cannot be used in the evaluation of the upper limb, where external forces are frequently absent and gravitational and inertial forces can only be estimated to describe the joint forces and joint moments. This leads to a less accurate description of kinetics in the upper limb (30). Only a few palpable anatomical reference points can be used when defining the ulna and radius, so other bony landmarks are needed (32). The applied markers on the skin can't distinguish between the radius and the ulna which decreases the accuracy of the calculations as well (30).

That's why up to now, no consensus is reached on which biomechanical model should be used for the kinematic evaluation of the upper limb (29–31,33). This shows the high need for a standardized procedure in the quantitative assessment of upper limb movements to monitor the outcomes of interventions in the upper limb, evaluate treatment and monitor follow up (29,30,34). Several options have been proposed but so far, none of them have been implemented in routine clinical assessments. These proposed models differ in the number of segments used, in a single or multijoint approach, in marker placements, in the selected set of tasks, in a segmental or functional approach,… which makes it hard to compare these models and their results. The complexity of the arm and its movements make it difficult to define a standard, easily applicable biomechanical model and a set of functional and clinically relevant tasks (29–31). These tasks can be extracted from daily life activities or they can be composed for the assessment and can consist of one specific movement or several cyclic repeats of a movement. Recommendations on, among other things, the joint coordinate systems have already been published by The International Society of Biomechanics (ISB), but these guidelines are often not applied in upper limb kinematic studies (31).

The role of EMG

Involving EMG electrodes in the 3D motion analysis could provide objective information on muscle activation and coordination (24,30,35). This way, more insight on the timing of and the interaction between agonist and antagonist muscles can be obtained, which is clinically relevant information for the treatment and follow-up of CP patients. Also, the occurrence of co-contractions during movement and the ability of selective activation of muscles can be observed.

The surface EMG electrodes, chosen because of the superficial position of the muscles and the non-invasive intentions of this study, are attached to the skin, on top of the muscle of interest. It registers the summation of action potentials fired by a contracting muscle as electrical activity (30,36). Attention must be paid to the possibility of cross talk. The surface electrode registers the action potentials within its field of interest. However, these action potentials could come from muscle fibers that are located next to the muscle of interest (30,36).

In this protocol the muscles of interest are the PT and the BB, because of their role in pro- and supination. Only these two muscles are provided with EMG sensors. Co-contractions of surrounding muscles like the Brachialis muscle for the BB and the Flexor Carpi Radialis, the Palmaris Longus and the Brachialis muscles for the PT could thus lead to the presence of crosstalk at the BB and PT electrode sites. Applying electrodes to these surrounding muscles as well could provide more information on co-contractions and (pathological) movement strategies. The activity of the Supinator and the PQ muscles was not explored, since these are deep muscles and are not accessible with surface EMG. Besides, even in typically developed subjects, the BB is a stronger supinator than the supinator muscle (1). Because the muscle of interest was only verified by palpation during a resisted movement, placement of the EMG electrode could be inaccurate.

Surface EMG electrodes are only semi-quantitative. The amplitude of the registration depends on the thickness of the intermediate layers separating the electrodes from the muscle as well as on the impedance of the skin, interelectrode space and their position relative to the underlying muscle (30).

It is clear that adding EMG registration to the quantitative assessment of the upper limb has important consequences for treatment planning too, as it could serve as a guidance for training weakened muscles or for botulinum toxin A injections into an overactive or spastic muscle. It offers a better perspective in understanding the impact of altered muscle function on the movement deficits and eventually will add to the clinical decision-making process (24,30).

Conclusion

This study aims to establish a protocol to evaluate pro-and supination in an analytical and functional context in children with CP. Differences in approaches between published studies make it difficult to compare results as different kinematic models and different tasks are used. At this point, there is no reliable and objective outcome measurement, comparable to gait analysis in the lower extremity, available for the upper extremity (3,12). No consistent guidelines and routines are provided in the clinical literature about how upper extremity movements should be investigated. This suggests the need for standardized protocols and a common approach to evaluate the upper extremity function, using kinematics and EMG data to support clinical and therapeutic decisions to improve forearm rotation and consequently upper limb function in children with unilateral cerebral palsy (3,13,22).

By breaking down the complex movement patterns of the upper limb and focusing only on pro- and supination, this study hopes to obtain a clearer view on rotation deficits of the forearm and their consequences on functional limitations in the patient's daily life. The goal is for the methodology to be used to offer quantitative objective information to the task of examining and

scoring patients' upper limb performance and ability. This necessitates comparison of several well defined parameters between typically developing children and CP patients during analytical pro- and supination cycles and during functional tasks that require forearm rotation. The goal is to obtain a better understanding on how the pro- and supination ability varies between patients, between the dominant and the non-dominant hand and between patients and typically developing children. This in order to focus therapy, improve function in daily life activities and integration into society.

Materials and Methods

The lab and materials

For the analysis of the movement of the upper limb a 24 camera 3D movement analysis system (*VICON Motion Systems, Oxford, UK*) was used. These 3D system cameras are hanging 2.2m above the ground in a 2.5m diameter circular composition. The cameras have a resolution of 16 megapixel and data was sampled at 100 frames per second. The camera incorporate LEDs which send out pulsed infrared light which reflects off the 3D retroreflective markers positioned on the patient's skin. In addition to the 3D cameras, 4 video cameras are used to capture video footage of the actual movement synchronously with the 3D and EMG data. Three of these cameras are used to record the view of the subject in the anatomical planes. The fourth camera films in an approximate 45° angle to the subject's frontal and sagittal plane in order to record the subject's ventral right side. This camera is placed approximately 1m above the ground. A clear view of the details of both analytical and functional trials is thus assured. To record muscle activity 4 bipolar surface EMG sensors (*Trigno® sensors, Delsys™ Inc, Massachusetts, USA*) are used, 2 on each arm (*see infra*) in conjunction with re-usable miniature bipolar surface electrodes (*Gerionics™ Inc, USA*).

For the functional trial a ping-pong racket is used. The racket has a diameter of 10cm and a full length of 16cm. The length of the grip, which diameter is 1.5cm, is 5cm. The racket has two different colours, with 3 retroreflective markers placed on the border, 2 opposite to each other and one on top, to track the rotation of the racket with the 3D system (Figure 1).

Figure 1: Positioning of the ping-pong markers

Both a Tripp Trapp® (*Stokke, Ålesund, Norway*) and a height-adjustable stool (*Swippo, Hamburg, Germany*) are used (Figure 2) as appropriate for the patient's pathology. This in order to optimally control the patient's posture as they both can be easily adjusted in height and provide appropriate pelvic or trunk support. The Tripp Trapp® chair can also support the feet. When seated on the stool, the feet are supported by the ground. The armrests consist of a proximal and distal arm support (manufactured in house, see Figure 2). They are made in such a way that the height and width of both supports can be adjusted to fit the subject. The maximal height of the armrests is 83cm and the minimal height is 51cm. The minimal distance between the two supports is 10cm and the maximal distance is 38cm.

A triangular wooden wedge shaped box (manufactured in house, Figure 3) is used to calibrate the pro- and supination angles provided by the kinematic model. The slope angles of the triangle are 60°, 30° and 90°.

Figure 2: Height-adjustable stool and armrests

Figure 3: Triangular calibration device

Subjects

Participants were 12 patients (6 boys and 6 girls) with unilateral CP, between 6 and 14 years old. They were recruited in the Cerebral Palsy Reference Centre in Ghent, Belgium. Inclusion criteria were the diagnosis of unilateral CP with a minimal 'House' classification of 4 on the affected side. Details of the House classification can be found Table 1 in Attachment 2. Patients were excluded if they had a botulinum toxin A injection or surgery of the upper limb in the last 6 months. There were no specific exclusion criteria for patients with contractures in the upper limb, however none of the patients had contractures. The control group consisted of twelve age- and gender matched typically developing children, who had no history of musculoskeletal or neurological disorders. All subjects had to be able to comprehend the protocol instructions and have no impaired hearing or vision (Table 2). The informed consent form was signed by the subjects (older than 12 years old, Attachment 3) or their parents/guardian (when younger than 12 years old, Attachment 4) before starting the assessment. Ethical approval was granted by the local Ethics Committee of the UZ Gent (Attachment 5). Clinical information of the CP

patients is provided by Dr. Lauwagie. This information is necessary to be linked to the results of this protocol.

Table 2: Inclusion criteria of CP patients

✓ Cognitive capacity to understand the given tasks
✓ No significant visual restrictions
✓ No significant auditory restrictions
✓ Capacity to perform tasks (Minimum House 4 on affected side)
✓ 6-14 years old
✓ Informed consent
✓ Unilateral cerebral palsy

Retroreflective marker locations

To define and reconstruct the upper limb in the 3D movement analysis program *(Nexus® 2.6.1, VICON™ Motion Systems, Oxford, UK),* 10 retroreflective markers are applied to each arm. The styloid process of the radius (RST) and the ulna (UST) are chosen as anatomical landmarks and are defined on the left side by markers LRST and LUST and by RRST and RUST on the right side. On the dorsal side of the forearm (FA), at the midline between the styloid processes and approximately 3cm more proximal, marker [R\L]FA is applied. The last forearm marker [R\L]FA2 is placed on the forearm slightly more lateral than [R\L]FA and more proximal than the line between the styloid process in comparison to [R\L]FA, as seen in Figure 4.

Three markers ([R\L]HUM1, [R\L]HUM2 & [R\L]HUM3) are placed on the upper arm of both sides to form a triangular cluster from which to define a technical segment for the upper arm. HUM1 and HUM2 are placed towards the posterior and anterior part of the upper arm while the arms are relaxed in a normal standing posture. HUM3 is placed on the lateral aspect of the upper arm, below HUM1 and HUM2, as seen in Figure 5.

On the medial (MEP) and lateral (LEP) epicondyles of the humerus and on the tip of the acromion, markers [R\L]MEP, [R\L]LEP and [R\L]SHL are applied. The acromion marker is used to estimate the location of the glenohumeral joint centre in the horizontal plane. The position of these 3 markers in the reference frame of the technical upper arm segment is recorded in a static standing trial. 'Virtual' versions of [R\L]MEP, [R\L]LEP and [R\L]SHL are then created in the dynamic trials. 14 mm markers are used on the epicondyles, acromion and

upper arm whilst on the styloid process and forearm, the smallest retroreflective markers are used (3 mm diameter) so as not to impede functional tasks.

EMG sensors

Next to the 10 retroreflective markers, the arm is provided with 2 Trigno® wireless EMG sensor units (*Trigno® sensors, Delsys™ Inc, Massachusetts, USA*). The EMG registration of BB and PT muscle activity is recorded because of their role in supination and pronation (*see supra*). The sensors have a 10 mm inter-electrode spacing and are positioned according to the placement protocol defined by Basmajian and Blumenstein in 1980 and modified by Blanc, presented at the SIAMOC meeting in 2013. The EMG sensor that registers BB activity is centred on the belly of this target at the greatest bulge (see A in Figure 5). The electrodes on the PT are placed a short distance (typically 5 cm in an adult) along a line which starts in the medial epicondyle of the humerus and which is 45° to a line drawn through both epicondyles (see B in Figure 5). When placing the electrodes, it is important to palpate the muscle and to provoke a resisted movement, to make sure to obtain a correct placement of the electrodes as there always is the possibility of an anatomical variation of muscle location between subjects. The attachment sites are marked and shaved to reduce the electrical impedance at the skin–electrode junction. Positions of the retroreflective markers and EMG sensors are illustrated in Figure 4 and Figure 5.

The wireless pre-amplifier/signal conditioner units (2 Delsys Trigno™ Mini and 2 Delsys Trigno™ Standard sensors) have a bandwidth of 20 to 450 Hz with a common mode rejection ratio of greater than 80 dB. An overall system gain of 1000 was used to amplify the EMG

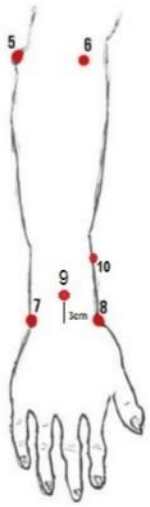

Figure 4: Placement of the retroreflective markers on the right arm. 5: RMEP; 6: RLEP; 7: RUST; 8: RRST; 9: RFA; 10: RFA2

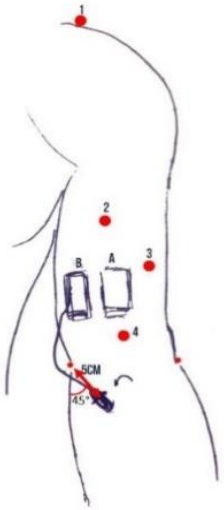

Figure 5: Placement of the retroreflective markers and EMG appliances on the upper left arm. 1: LSHL; 2: HUM1; 3: HUM2; 4: HUM3; A: EMG BB; B: EMG PT

signals. The analogue EMG (voltage) data from the wireless EMG system was digitally recorded using the analogue voltage input (analogue to digital converter) channels provided by the 3D motion capture system with data sampled at 1000 samples per second.

The protocol

General

All subjects are asked to perform a protocol consisting of several exercises. The first part consists of analytical exercises, in which only the movement of interest is performed and in the second part some functional tasks are performed. All assessments are captured with the 3D motion analysis system, the EMG registration and the video cameras at the same time. The hand-to-head exercise is developed by thinking of daily life activities requiring pro- and supination and by breaking these activities down to the pro- and supination part. The clapping exercise is chosen for describing bimanual function, which is an important part of daily life activities. To study the effect of speed and holding an object, the ping-pong exercise is designed.

Every movement of the subject's arm in the trials is evaluated using the kinematic and EMG data obtained during different recordings of various exercises. Before starting an exercise, instructions are given to the subject on how to perform the task. Next, the exercises are demonstrated by the observer and the subject is asked to try the exercise once before the recording starts to ensure that the subject understands the task. When the subject fails to perform an exercise properly, he/she is given another try.

Each task is repeated 3 times, except for the static trial and the maximal voluntary contractions (MVC) which are only done once. By repeating the exercises more than once it is hoped to measure the subject's best possible performance, as the subject will not reach the same speed and active range of motion (AROM) in every trial. The minimum, maximum and average values for each parameter are extracted across all repetitions of one exercise.

The MVC is only repeated once because of the muscle fatigue it causes in both CP patients and typically developing children. The recording in Nexus *(Nexus® 2.6.1, VICON™ Motion Systems, Oxford, UK)* starts a few seconds before the subject starts the exercise and ends once the exercise is completed. This guarantees all movements are captured.

Static trial

Standing in the middle of the lab, the subject stands as motionless as possible for at least 5 seconds while holding both shoulders slightly abducted and at 30° anteflexion with the elbows in 90° flexion. The wrists are in a comfortable pronated position, fingers in extension and feet flat on the floor. This trial is used to record all marker positions in the reference frame of the upper arm. The static trial allows the creation of a model of the subject, used in subsequent

trials, which expects every marker in a certain position and allows reconstruction of lost or removed markers. This is necessary because the retroreflective markers may not be present or accurate due to skin movement during the dynamic trials.

Analytical trial

Bimanual

The subject is seated in an upright position on a height-adjustable stool (Figure 2). Feet are flat on the floor and knees are in 90° flexion. Both forearms are supported by the armrests, with the rear support approximately 2 cm distal to the elbow. The elbows must approximate a 90° flexed position with the shoulders slightly abducted and the palmar side of the hand facing down.

The bimanual analytical exercise consists of isolated movement tasks. The subject performs, starting from a pronated position, a supination and subsequently a pronation with both hands at the same time. This supination-to-pronation cycle is repeated 4 times within one trial and the subject is asked to perform at a self-selected speed. However this speed could be influenced by the observer. The focus is on performing the cycles in a controlled way and with the largest range possible. This data collection of 4 cycles is repeated 3 times with only a slight pause between data trials.

AROM is one of the parameters to be derived from the bimanual analytical trial, it is a measure for the range of motion the subject can reach himself and is measured in degrees. For all trials, this means for all 9 completed cycles, the maximum degree of supination and pronation of both hands is calculated and the mean range of all sup- and pronation cycles is evaluated for each individual.

Secondly, average peak angular velocity is calculated in radians per second for pro- and supination separately. The maximum value for the angular velocity is extracted for pronation and supination for each cycle within the trial separately. Each trial thus results in three maximum angular velocity values for pronation and three maximum angular velocity values for supination. For the 3 trials a total of 9 values are thus derived. The mean value for maximal pronation angular velocity and for maximal supination angular velocity is then calculated. Mean angular velocity during pronation and the mean angular velocity during supination is measured for each cycle allowing trial and multiple trial summary statistics to be derived.

Average peak angular acceleration measured in radians per second per second is also extracted as a parameter from the data. This value is extracted from each cycle within the trail in the same way as the velocity parameter. This means that the maximal value for acceleration is derived for every pro- and supination movement separately and that the mean value of these separate measurements is noted.

Jerky movements are seen as an indirect measure of muscle coordination and are measured in this study by calculation of the area underneath the absolute acceleration curve. A mean value of all 3 trials is calculated as an index of 'jerkiness' with lower values consistent with slower and smoother movement.

Next a supination over pronation ratio is calculated for all parameters mentioned above. This parameter indicates the difference between the pronation and supination movement showing, at a glance, which movement is performed best by the subject. It is calculated by dividing the absolute supination value by the pronation value of the same parameter.

To calculate the symmetry index, data of the dominant arm are compared to those of the non-dominant side for each parameter listed above. The value of the parameter of the non-dominant side is divided by the value of the same parameter on the dominant side.

We expect patients to have a smaller AROM in their affected hand, compared to their unaffected hand and compared to the non-dominant hand of the age- and gender matched control, mostly because of a limited supination ability. The AROM of the unaffected hand is expected to be similar to the AROM of the dominant hand of the age- and gender matched control. We also expect a slower angular velocity of the affected hand, compared to their unaffected hand and compared to the non-dominant hand of the age- and gender matched control, especially for supination. When compared to the dominant arm of the control, we expect the angular velocity of the unaffected arm to be similar. For the angular acceleration, our expectations are that it will be similar for the control's dominant hand and the patient's dominant hand. We anticipate that the patient's non-dominant hand would have a lower value for acceleration than the control's and we expect the 'jerk index' to be worse in the subjects with CP in their affected arm compared to their control's non-dominant hand. Both the dominant sides of patient and control are expected to have similar jerk indexes. Our expectations are that the supination over pronation index will be smaller on the patient's affected arm compared to the control's non-dominant arm and that the indexes of the dominant sides will be similar for the patient and the control. For symmetry we expect, especially the children with CP, a dominance of their unaffected side. The control might have a slight dominance of the dominant side.

Unimanual

The subject performs the same movement cycles as in the bimanual analytical trial, but only using one arm. The dominant side is analysed first, followed by the non-dominant side. As in the bimanual tests both forearms are supported and each of the 3 trials consists of 4 supination-to-pronation cycles.

We expect the same results as in the bimanual trials for the comparison of the patient's dominant arm with the control's dominant arm and the affected arm of the children with CP with the non-dominant arm of the control. For the control, we expect similar values in both the unimanual and bimanual exercise, with maybe a slight advantage of his dominant hand in the unimanual exercises. The parameters of both the unilateral and bilateral analytical trials can be reviewed in Table 4 in Attachment 6.

Functional trial

Calibration

The axis for evaluating pro-and supination angles used in this paper is not the same axis as used in clinical examinations. In a clinical setting the angles are derived from the position of the hand, whilst standing in neutral position i.e. elbows 90° flexed, shoulders 0° abducted/anteflexed and the palms facing medial with the thumbs 0° abducted. In this study, because of the marker placement on anatomical reference points such as the epicondyles, the supination and pronation angles are described in reference to a precise axis at the elbow.

To define the angle of pro-and supination two coordinate axis systems are defined: one in the humerus (with its origin in the elbow) and one in the forearm (with its origin in the wrist) of the subject.

The first axis in the humerus is defined from the elbow joint centre to the shoulder marker (through the glenohumeral joint). The elbow joint centre is defined as the midpoint between the epicondyle markers. The second axis with origin in the elbow joint centre and perpendicular to the plane of medial epicondyle, lateral epicondyle, elbow and wrist joint centre points anteriorly (when in the anatomic position). The third axis is the line perpendicular to the first two axes completing a right hand co-ordinate system .Thus the third axis runs from the elbow joint centre laterally and close to but not necessarily through the lateral epicondyle.

The coordinate system of the wrist consists of a first axis running from wrist joint centre to elbow joint centre. The wrist joint centre is defined as the midpoint of the markers on the styloid processes. The second axis of the wrist is perpendicular to the plane of the markers on the styloid process and elbow and wrist joint centres, with origin in the wrist joint centre pointing anteriorly when in the anatomic position. The third axis of the wrist has origin in the wrist joint centre and points laterally close to but not necessarily through the radial styloid.

By constructing the coordinate systems of the elbow and wrist in this manner, the angles of pro- and supination can be derived from the rotation of one axis system relative to the other using the convention of Grood and Suntay (1983) with the flexion/extension axis on the elbow joint fixed in the humerus and rotation (thus pro- and supination) axis fixed in the wrist/forearm (37). This allows calculation of the pro- and supination independent of the position and

orientation of the arm in space. This allows measurement of pro- and supination with no constraint on the position or orientation of the subject in the laboratory space.

The neutral position is described as the position in which the line through the styloid markers is in the same plane as the flexion/extension axis of the elbow (in the humerus). By convention, pronation is reported as a positive angle and supination as negative. The angles generated from these axes will not correspond 100% to clinically understood angles of pro- and supination, which are both described as positive and in which negative angles reflect incapability of performing the required rotation.

Before the start of the functional tasks, the angles of the wrist and hand are to some extent calibrated using a triangular wedge shaped box (see Figure 6). The hand and wrist are placed flat on the calibration device at an angle of 60° pronation, this trial is done once for the left hand and once for the right hand. The second angle used is 90° pronation which means placing both hands flat on the table with the dorsal side of the hand facing upwards. A quick trial (+/- 6 seconds) is recorded while the subjects hold their hand in each of these positions.

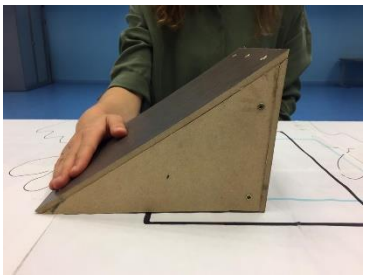

Figure 6: Calibration device put to use

The angles derived from the calibration trials can be compared to those generated during the dynamic trials to give a more clinical interpretation of the outcome. The calibration wedge has two potential roles: to check if an AROM, measured with the wedge for two different angles, is related to that derived using the 3D kinematic model and to see what offsets there are between kinematic model derived angles and clinically judged angles.

Ping-pong

This unimanual trial is performed while the subject is sitting on a height-adjustable chair in front of a table. The subject's feet are resting on the floor or on the foot support with the knees in 90° of flexion. The use of a ping-pong racket is required for this exercise. The subject's fingers have to be wrapped around the grip and the thumb must be in an upward position as far as is possible (see Figure 1). The elbow of the arm under test is resting on the table and the wrist is lifted off the table so the forearm makes an approximate 20° angle with the table. The non-performing hand is resting on the table at shoulder width, with the palm of the hand facing

down. The trials focus on the dominant arm first and then the trials are repeated with the non-dominant arm.

Two static trials are recorded. In the first trial the subject is asked to perform a maximal pronation while holding the ping-pong racket, in the second one to perform a maximal supination. These positions are held for 6 seconds if possible.

Subsequently the 3 trials of the core exercise can start, in which the subject is asked to start in maximal pronation and then alternate between pro- and supination as fast as possible during 5 seconds and while holding the ping-pong racket. The alternation between pro- and supination is displayed by the visible alternation between the two colours of the racket, as judged by the subject. The subject is asked to only initiate the exercise when a verbal starting signal is given by the instructor. In order to define a standardized dataset the starting time is demarcated by the uncovering of a 3D retroreflective marker by the instructor and the ending point is defined when, 5 seconds later, the marker is recovered. This way a record of the trial length is transferred to the 3D data. Subjects are asked to start the exercise with a verbal signal and cannot see the (un)covering of the marker.

Whilst performing the exercise the instructor must verify that the exercise is executed correctly and that the subject alternates between the two colours of the racket. Focus in this exercise is on speed and the subjects are encouraged to go as quickly as possible.

The maximum range of motion is measured as the maximum pronation and maximum supination in the static trials of each arm. These trials are necessary because holding an object can affect the ability to pro- and supinate. This makes the angles derived from the analytical exercises unreliable as the AROM might be smaller than the AROM measured in the analytical trials.

Next AROM is also measured during the ping-pong exercise itself. The maximum values for each supination and pronation cycle are extracted separately from the trial data. The mean AROM of full pro-to-supination cycles is also measured.

Mean angular velocity is calculated in radians per second. This is measured for pro- and supination separately. Speed, and the ability to pro- and supinate can also be judged by the amount of completed cycles. One full cycle is measured between 2 supination peaks. Average peak angular acceleration is measured as the mean of all acceleration peaks throughout all 3 trials with pronation (positive) and supination (negative) calculated separately.

To measure deadtime - the delay in movement between the verbal starting signal and the beginning of the movement - the number of video frames between the uncovering of the extra

retroreflective marker and the start of the movement (judged from pro-supination kinematics) are counted.

Symmetry is evaluated comparing the left and right side for all the parameters listed above. The values of the non-dominant/affected side are divided by those of the dominant side for the same parameter. The parameters can be reviewed in Table 5 in Attachment 6.

We expect the AROM to be smaller in the affected hand of the patients compared to their control's non-dominant hand. Especially for supination, we expect it to be restricted due to weakened supinator and BB muscles and spastic PT and PQ muscles. Our expectations are that the dominant sides of the patient and the control will perform equally.

Comparing the velocities, we expect subjects with CP to complete less cycles with their affected hand when compared to the non-dominant hand of controls as we expect their angular velocity to be slower. Our expectations are that the number of completed cycles will be similar for both the unaffected hand of CP patients and the dominant hand of controls. We expect deadtime to be longer for the affected hand of CP patients compared to the non-dominant hand of their age- and gender matched controls.

We expect that patients will have a lower acceleration in their affected arm compared to their control's non-dominant arm. The acceleration values of the dominant side of the subject with CP and his control are expected to be similar. We expect that the deadtime will be similar for the dominant arms of the patient and control. For symmetry, our expectations are that the controls will have a slight advantage for all parameters in their dominant arm over their non-dominant arm. We expect subjects with CP to have greater dominance of their unaffected side compared to their affected side.

Hand-to-head

The subject is seated on a height-adjustable chair in front of a table to perform this exercise. The feet are flat on the floor or on the foot rest with knees in 90° of flexion. The starting position of the hands on the table is marked on the table surface at approximately shoulder width and at one forearm's length, measured from the border of the table closest to the patient. To start, both hands are lying on the table with the palms facing down. A marker is placed on the forehead of the subject and is used as a reaching target for the subject. This unimanual task is repeated 4 times within each of the 3 trials, first on the dominant side and subsequently on the non-dominant side. The non-performing hand remains at rest on the table in the starting position.

The observer instructs the subject to start with the palm of the hand on the starting spot and then to touch the forehead in order to cover up the marker. It is not explicitly stated that the

goal is to reach the forehead in supination, although it is demonstrated this way and subjects reaching the forehead in pronation are not corrected. When the marker or forehead is touched, the hand returns to starting position. This is repeated 4 times within each of the 3 trials. The exercise is performed at a self-selected speed and the subject is encouraged to do it in as controlled a way as possible. In this study, this exercise is only scored as successful when the forehead is reached in supination, as judged by the graphs, the video footages and the disappearance of the forehead marker in Nexus.

One of the parameters extracted from this exercise is AROM, measuring the maximum pro- and supination peak of all 3 trials and the mean range of pro- and supination in these trials. Whether or not the task is completed successfully is scored by two independent observers, to reduce subjectivity. A symmetry index is calculated by dividing the values of the non-dominant arm over the dominant arm for each parameter. An overview of the parameters can be found in Table 6 in Attachment 6.

We expect CP patients to have a smaller AROM in their affected hand in comparison to the non-dominant hand of controls. We also expect the AROM of the unaffected hand to be similar to the AROM of the dominant hand of controls. Due to their smaller expected AROM, patients are less likely to successfully complete this task with their affected hand compared to the non-dominant hand of their age- and gender matched controls. We expect the success of the exercises to be similar for both the unaffected hand of the patients and the dominant hand of the controls. For symmetry, again we expect this will illustrate better performance of the dominant hand over the non-dominant hand, especially in patients.

Clapping

The last task is performed bimanually. The subject is seated on a height-adjustable chair with his feet flat on the floor and knees in 90° flexion. Both arms are in the same starting position as in the hand-to-head exercise. In the middle of the distance between both palms, a line is drawn which reflects the subject's median axis.

The subject is instructed to bring both palms together at the midline, in this way a supination movement is performed between the starting position and the clapping position. The ulnar side of the hand must keep touching the table and the subject is instructed before the start of every trial to do so. When both hands have touched, the subject is instructed to return to the starting position, so they perform a pronation between the clapping position and the starting position. This cycle is repeated 4 times in one trial at a self-selected speed. The test is repeated 3 times.

Focus is on symmetry of the supination and on the central alignment of clapping. This means that both hands should move equally lateral to touch at the midline and should supinate equally.

Parameters to calculate the AROM extracted from this exercise are the same as in previous exercises. “Move to midline” is an extra parameter measured for this exercise. It is calculated in millimetres by measuring the distance of the RST marker to the midline at the clapping time. This midline is defined as the middle of both shoulder markers. Distance to the midline is a positive value and becomes negative for the hand that crosses the midline. Symmetry index is gathered from comparing the non-dominant hand to the dominant hand. The parameter overview is formulated in Table 7 in Attachment 6.

We expect to see that the dominant side of the patient compensates for the affected side. This means that we expect to see a smaller AROM in the patient’s affected side compared to the control’s non-dominant side. Our expectations are that the dominant hand of the patient will have a greater AROM than the dominant hand of the control. The distance to the midline is expected to be smaller on both sides of the control compared to the subject with CP. We expect the patient’s affected arm to move less to the midline and thus result in a greater distance to the midline than the control’s non-dominant hand. As we expect the dominant hand of the patient to move over the midline to compensate for the affected hand, the distance is expected to be negative and to be greater compared to the control’s dominant hand. We expect symmetry indexes to be close to 1 for the control in all parameters. For the patient a dominance of the unaffected hand is expected.

Maximal voluntary contractions (MVC) and EMG

Finally, maximal voluntary (isometric) contractions against resistance are performed for both the BB and the PT. Supination is performed against resistance to measure the MVC of the BB and pronation is resisted for the measurement of the MVC of the PT. Firstly on the dominant side, secondly on the non-dominant side.

An MVC is necessary to quantify the level of muscle activation during specific movements. It allows normalization of the EMG in the other trials and to express these EMG data as a % of the MVC. The EMG registration allows comparison of the timing of muscle activation between different subjects and between different muscles and allows the evaluation of the presence of co-contractions.

Processing the data

Labelling the markers and constructing a model

The 3D reconstruction of the marker trajectories and labelling of the trajectories is carried out in Nexus via a range of semi-automatic software tools/sub-modules. Correct labelling of the static and dynamic trials is essential for accurate modelling.

The labelled trajectories are filtered to reduce noise and movement artefacts which have frequencies higher than are likely physiologically. The custom (in-house) written plug-in Static

and Dynamic models Body Language are then applied to the filtered data to generate kinematics of the upper limb. These kinematic data must be checked for possible artefacts, such as impossible angles, gaps and other and when possible, these artefacts must be solved. The files containing the kinematics are read into Polygon (*VICON Motion Systems, Oxford, UK)* for display and export of the kinematics and its derivatives (velocity and acceleration).

Marking events on the graphs

In order to extract the chosen parameters key timing events must be identified for each task. Semi-automatic methods provided within Nexus are used to define the start and end of trial sections and key points within each cycle.

Results

Due to the limited timeframe of this thesis, it was not possible to perform statistic tests on all subjects. Rather we chose to compare one patient with a severe form of unilateral CP and his age- and gender matched control. A patient with a severe condition was chosen so that the differences in the parameter outcomes would be clearly visible. In this way a quick overview through which to cast a critical eye over the protocol is made possible. Angles between 0° and 90° pronation are described as positive, the negative angles reflect angles between 0° and 90° supination.

Clinical assessment of patient

First it is necessary to delineate the functional impairment of the patient by clinical assessment. The patient is an 8 year old boy with left unilateral CP who attends a regular school. At the age of 3-4 months the patient's parents started to notice he didn't use his left hand whilst grasping for objects. An MRI-scan of the brain showed an enlargement of the right lateral ventricle with loss of parenchyma (high in the thalamic region and in the most dorsal part of the intern capsule). There was also a hyperintense aspect of the periventricular white matter in the frontal and parieto-occipital part of the brain visible.

There is no sensation of pain or any abnormal sensibility. The patient has a GMFCS 2, MACS 2 and a Modified House 5 score. Observing his upper limb, it is noted that full passive supination is possible, whilst active movement is nearly impossible. There is spasticity in the PT muscle, which is scored 2 on the modified Ashworth scale. The supination strength is less than 3/5 on the Medical Research Council (MRC) scale for muscle strength, which means the patient can perform a supination against the gravitational force. The MRC scale for muscle strength can be found in Table 3 in Attachment 2. The patient is always looking for a way to compensate and bimanual activities remain a challenge. It is impossible for the patient to tilt heavy objects.

Results of the analytical trials

In Table 8 in Attachment 6 an overview of the descriptive summary parameters is given for the bilateral exercise and in Table 9 for the unilateral exercise. While going over these values it is important to compare the dominant sides of both the patient and the control, the non-dominant sides and the symmetry indexes. Interesting differences can also be seen comparing parameter outcomes of the unimanual exercises to those of the bimanual exercises.

Results of the functional trials

The parameters and their outcome values are listed in the tables in Attachment 6. For the calibration and static trials of the ping-pong exercise these can be reviewed in Table 10, for the ping-pong exercise in Table 11, for the hand-to-head trials in Table 12 and for the clapping exercise in Table 13. The same method used to look at the results of the analytical trials should be used going over the results of the functional trials.

Comparing functional AROM to analytical AROM

As AROM is the key parameter throughout all exercises it can be useful to compare the outcomes of the functional trials to the ones of the analytical trials.

The maximum pronation for the patient varies between exercises. For the bilateral analytical trials this is 62° for the dominant side and 55° for the non-dominant side and 66° and 54° respectively for unilateral analytical exercise. In the static trials of the ping-pong exercise the patient has a maximal pronation angle of 37° on his dominant side and 57° on his affected side. During the ping-pong trials the patient has a maximal pronation of 90° on his dominant hand and 53° on the other side. In the hand-to-head exercise the maximal pronation is 55° for the dominant side and 95° for the affected side. During the clapping exercise the dominant hand reaches a pronation of 81° and the non-dominant hand a pronation of 48°.

The maximal pronation also differs for the control. In the bilateral analytical trials the dominant hand reaches a pronation of 75° while the non-dominant hand reaches a pronation of 77°. In the unilateral trial they reach an angle of 70° and 78° respectively. In the static ping-pong trials a maximal pronation of 53° is reached on the dominant side and of 35° on the non-dominant side. During the ping-pong exercise, the maximal pronation seen is 86° on the dominant side and 78° on the other side. In the hand-to-head exercise the control performs a maximal pronation of 63° on his dominant side and 62° on the non-dominant side. For the clapping exercise these angles are 57° and 51° respectively.

Next the maximal supination is compared between the different exercises. First it is compared for the patient's data. In the bilateral trials this parameter is maximal at -61° on the dominant side of the patient and 26° on the non-dominant side. These angles are -64° and 33° respectively for the unilateral exercise. In the static trial of the ping-pong exercise, an error

occurred so the maximal supination could not be determined for the dominant arm of the patient. On the affected side the angle of maximal supination is 46°. During the ping-pong trials a supination of -77° is performed on the dominant side and one of 44° on the affected side. In the hand-to-head trials angles of -68° and 36° are retracted from the data respectively for the dominant and non-dominant side. The clapping exercise results in maximum supination angles of -47° for the dominant side and 29° for the affected side.

Second the different values for the maximum supination are compared for the control. The bilateral trials result in a maximal supination reached of -70° for the dominant hand and -61° for the non-dominant hand. In the unilateral trials the control is able to perform a supination of -78° on his dominant side and one of -63° on the other side. From the static trials of the ping-pong exercise a maximal supination angle of -74° is retracted on the dominant side and an angle of -28° on the non-dominant side. Respectively these angles are -78° and -76° during the dynamic trials of the ping-pong exercise. In the hand-to-head trials the subject performs a maximal supination of -62° on the dominant side and -44° on the other side. The clapping exercise results in values of -37° and -40° for maximal supination on the dominant and non-dominant side respectively.

The mean range of the AROM is also compared between the different exercises. The patient's mean range is 112° (SD 4.3) on his dominant side and 12° (SD 3.7) on his affected side for the bilateral analytical trials. In the unilateral exercise the patient performs a mean range of 121° (SD 5.8) and 12° (SD 2.6) on the dominant and non-dominant side respectively. From the ping-pong exercise ranges of 142° (SD 11.5) and 3° (SD 2.3) are retracted for the dominant and non-dominant side respectively. In the hand-to-head trials mean ranges of 114° (SD 3.8) on the dominant side and of 40° (SD 14.9) on the affected side are found. The ranges of the clapping exercise are 84° (SD 10.9) on the dominant side and 9° (SD 4.4) on the non-dominant side.

For the control the mean range on the dominant side is 134° (SD 8.1) and 129° (SD 6.1) on the non-dominant side for the bilateral analytical trials. The unilateral exercise results in a mean range of 137° (SD 5.8) for the control's dominant side and a mean range of 129° (SD 5.7) for the non-dominant side. In the ping-pong exercise the subject reaches a mean range of 134° (SD 29.7) on his dominant side and a mean range of 119° (SD 15.8) on his non-dominant side. On his dominant side the control performs a mean range of 105° (SD 8.1) in the hand-to-head exercise. On his non-dominant side this range is 92° (SD 6.7). The mean ranges extracted from the clapping exercise are 74° (SD 6.8) and 67° (SD 7.5), on the dominant and non-dominant side respectively.

Discussion

This study proposed a model for a quantitative assessment of pro- and supination of the forearm in children with unilateral cerebral palsy. Both kinematic analysis and EMG registration were applied in this comparative analysis between children with cerebral palsy and typically developing children.

The lab and materials

The arm rests used in this study are homemade, but are easily reproducible. Both width and height of the proximal and distal armrests are adjustable to the subject's needs. While performing the assessment, the following question was encountered: is it better to apply symmetrical heights or should the armrests be adjusted for each arm separately? In this assessment, the arm specific approach was chosen. That way every subject was most comfortable and each arm had a solid and tailored support. The most obvious differences in the height of the armrests are seen in the cerebral palsy patients, these can be explained by the hypertonia which can interfere with muscle length and growth.

For every subject and for every trial, the best fitting chair was chosen and adjusted to the subject's height. Every subject was thus asked to perform in the most comfortable position. Bigger children used the stool for both the analytical and the functional task, while smaller children often switched to the Tripp Trapp® for the functional part of the assessment. Seated in the Tripp Trapp®, their feet were supported and the chest was at table height. Feet are supported by the ground when children are seated in the stool. The one major difference between the stool and the Tripp Trapp® is that the stool has no back support, which could make it harder for subjects to remain an upright position during the assessment. Using the Tripp Trapp® in the analytical trial was impossible as the armrests did not fit underneath the chair, that's why the stool was chosen for this part of the trial.

The calibration device consists of different angles. The 60° pronation angle i.e. the 30° angle of the device was chosen for calibration because patients have less difficulty performing a pronation of the forearm than a supination. The other calibration angle used is 90°, when both hands are flat on the table with the palm of the hand facing down. Using two different reference angles makes it possible to compare this range of motion to the model output.

The smaller markers with a 3mm diameter were used on the forearm of the subjects as it is more elegant on this small surface. Their smaller size allows a more correct placement which will not interfere with movement and makes it less likely they will be mixed up during the reconstruction by Nexus. The larger markers with a 14mm diameter are used on the upper arm, as markers on these locations have a greater chance of being covered by the EMG devices and the elbow support. However, all of these markers do not have the same

measurements as the anatomical reference points, which could lead to non-exact repositioning when a marker needs to be reattached after falling off.

The size of the handle of the ping-pong racket is also a point of discussion. In this assessment, a rather small racket with a 10cm diameter and a grip length of 5cm was used. Children with grip difficulties or bigger hands encountered some problems while performing a trial of fast cycles holding this small object. It is suggested that 2 sizes of rackets are used in the future: a small racket for small children and a bigger racket for the bigger children.

Subjects

The analysed subjects in this study were 12 patients with unilateral CP and 12 typically developing children, which is a small sample size. One control subject was excluded from the study, before processing, because of many incorrect trials and thus useless data. A substitute was sought to fill in, resulting in a total of 12 usable sets of normal data. Subjects were extremely motivated volunteers. The implementation of this protocol in routine clinical evaluation could be challenging when assessors are confronted with patients coming for routine assessment, as these patients regularly have to attend hospital visits and might therefore be less motivated to come in after a whole day of doctor appointments.

Retroreflective marker locations

Markers were placed along the wrist, the forearm, the upper arm and the shoulder of the patient, in a way that reconstruction of the upper limb in Nexus was possible (*see supra*). These locations were chosen by trial and error, after experimenting with different positions.

The trial and error method was especially needed for positions FA1 and FA2. First these markers were both placed on the dorsal side of the forearm, which lead to missing markers in a supinated position but with markers on the ventral side lost during pronation. Therefore it was chosen to apply the FA2 marker on the transition of the ventral to the dorsal side of the forearm and the FA1 marker on the dorsal side of the forearm. This ensured better visibility of at least three of the four markers in the supinated position which allowed the reconstruction of the missing 4th marker from the location of the other three.

There is an important difference in arm length between the oldest subjects and the youngest which must be kept in mind when placing the markers and the electrodes. A smaller arm requires placement of the markers closer to each other and makes it harder for Nexus to distinguish between different markers, which could lead to a distorted graph. Adjustment of the FA2 marker might be required to obtain better tracking. In this trial, the location of this marker on the forearm varied between 6 to 8cm proximal to the line connecting both styloid processes. It is suggested that in further studies, the location FA2 marker is defined by a fixed percentage of the forearm length.

Even though anatomical reference points are used, the reconstruction of the upper limb is not completely reliable since skin movement is unavoidable. Therefore the markers on the epicondyles must be applied when the elbows are in a 90° flexed position as this is the position most exercises are performed in and this minimalizes the effect of skin movement on the position of the marker relative to its anatomical position. The position of the FA2 marker is subject to skin movement too. However no good alternative was found for this marker's position as the skin movement allows it to be seen in pro- as well as supination.

While processing the data, only minor tracking problems occurred. In one subject, one of the humeral markers became covered by her hair during the hand-to-head trails, which made it difficult to reconstruct the upper arm axis in this exercise. Care must be taken to ensure that the humeral markers remain visible during the required functional tasks. An alternative is to add additional markers but it must always be ensured that all markers are present in a static trial.

The trial of maximal supination before starting the ping-pong exercises was the hardest one to reconstruct and label in every subject, because the markers on the dorsal side of the forearm were invisible for the camera system in this position. As the missing markers never appeared in the trial, the system was unable to reconstruct them. This suggests a change in the trial is of interest: starting from a neutral position to a maximal supination or performing a maximal pro- and supination in the same trial might solve this issue as this guarantees visibility of the markers at least once. This might imply the need for more markers covering the forearm.

EMG sensors

Placement of the EMG sensor on the BB is easy because of the superficial location of this muscle and the visibility of its belly during contraction. Locating the PT is more challenging. The assumed location of the muscle must be confirmed by palpation during a resisted pronation and, after attaching the sensor, by visual control of the EMG graphs during a resisted movement. The placement of the electrodes might have been inaccurate in some subjects, because the assessors had no experience in placing EMG electrodes.

The indicated 5cm distance from the medial epicondyle differs in patients with smaller arms and only serves as an indication for the placement rather than the precise localization. As mentioned above, the possibility of cross talk at the EMG site must be taken into account. To minimize the possibility of cross talk, EMG electrodes could be attached to all the surrounding muscles. But these muscles do not have a supination or pronation moment or they are not accessible with superficial EMG electrodes.

The protocol

General

The patient performed a mean range of motion of only a few degrees. This small range can be due to noise and has no meaning. It should be interpreted as the fact that the patient is unable to perform any rotation on his affected side. This correlates with the clinical assessment, where it was noted that the patient was unable to perform any active supination.

At the same time of the forearm pro- and supination assessment, there was a movement analysis of the subject's wrist flexion and extension. This implied more markers on the hand and extra EMG electrodes on the arm which could have compromised visibility of the markers. It also occupied a significant part of the arm, leaving less space for any extra markers or EMG electrodes. For future studies of the shoulder for example, this must be kept in mind.

Also, because of this additional analysis, assessments took longer than only the time needed for this study. The duration of the complete assessment was between 1.5 and 2 hours, of which 30 – 40 mins was needed for preparing the subject. In some assessments there were additional computer, camera or sensor problems which extended the duration of the analysis and tested our subjects' patience. The estimated time for only the pronation and supination analysis is 45 mins, including marker and EMG sensor placement. Limiting the assessment time is an important point of discussion, because it can improve the subject's motivation and thus his performances. When the analysis takes too long, the subjects get bored and are more likely not to perform to their maximal capacities.

Every exercise starts in pronation. This starting position makes it easier for CP patients to perform the tasks as they often have spastic pronator muscles, which makes supination difficult. Beginning an exercise in supination or in a neutral position could therefore demotivate the patients as they might not be able to reach this starting position and they might feel like they failed before the exercise starts. Every exercise was first performed on the dominant side and subsequently on the non-dominant side. The fact that the dominant hand was examined first could result in better outcomes for the non-dominant hand because the subject is then already 'trained' in performing the exercise.

Demonstrating the exercises and performing at the same time as the subject could alter the subject's speed and AROM because the subject could have a greater AROM or a higher maximal velocity than the observer. However, good demonstration of the tasks is necessary to achieve correct execution of the exercises. Attention must thus be paid when demonstrating the trial not to underestimate the subject's capacities by going too fast or too slow, since the subject might not reach its maximum range or velocity.

In the first try outs of this protocol, which were mainly performed on adults, the movement cycles were only repeated three times. When processing these subjects, graphs were often not sufficient to judge these three repetitions as full cycles. That's why, in the following assessments, every exercise was repeated 4 times in order to capture every supination-to-pronation cycle and visualise every transition from pro- to supination and vice versa within these cycles allowing the interpretation of 3 movement cycles.

As stated above, the subject will not reach the same maximal values for the parameters in subsequent trials due to their variable level of concentration and motivation but also because of normal variation. By repeating the task several times, it is hoped to capture the subject's best possible performance, but children will often lose focus over time. It is possible that the exercise that is performed last does not display the subject's actual capacities. However it is also possible that the first trial underestimates the subject's capacities due to the fact that the exercise and thus the movement is new to the subject. Also, not being able to accomplish a task might be an additional demotivation. Three repetitions may cause both mental and muscle fatigue and thus may lead to less accurate results. However, verifying mental and muscle fatigue was not within the scope of this study. A child with CP might have to focus more to achieve a certain movement, resulting in a higher level of fatigue. During the assessment, it was clear that younger subjects were easier distracted than older subjects. Subjects had to be able to understand and execute the tasks and the young age of some subjects could explain some differences in results between younger and older subjects that might become apparent in the future analysis of the captured data. Further investigations in minimising repetitions are necessary in order to limit assessment time.

Accurate and clear communication between the observer behind the computer and the instructor who takes care of the subject is very important. The observer must inform the instructor the recording has started, without informing and thus preparing the subject. Both the observer and the instructor must keep an eye on the correct execution of the exercises, the correct positioning of the subject in the chair and the position of the arms in the arm rests or on the table, the visibility of all markers and so on. It is important to give clear instructions, which are the same for every subject.

It is important to note that the negative angles used in this study reflect the range of the performed supination and the positive angles reflect the range of pronation that was performed by the subject. This approach is used in the data analysis program and enables the display of sinusoidal graphs. However, in a clinical setting, negative angles reflect deficits and thus mean that there is a shortage of range.

Analytical trial

In the analytical trials the position of the subject is very important as good positioning generates the opportunity to reach maximal performance. When using the armrests it is important to check that the EMG devices are not stuck between the subject's arm and the armrest.

Results of the analytical trails

The results of the comparison of the dominant side of the control with the unaffected side of the patient for the bimanual exercise are as expected. No clear differences are seen in AROM, velocity, acceleration or smoothness. When differences would be detected in this comparison, results of the patient could be worse, due to coordination difficulties, or they could be better, due to their capacity to compensate for the lack of movement on the affected side. It is suggested to compare these parameters in a larger population, to check the consistency of the results found in this study.

When comparing the results for these parameters on the dominant sides in the unimanual exercises, no clear differences for AROM and smoothness are seen as well. The velocity and acceleration for pronation and supination are both slightly higher in the control than in the patient, but this could be a normal variation. Comparing the results of the unilateral exercises to the bilateral exercises, in both the patient and the control, a greater AROM (except for pronation of the control), a higher velocity and a higher acceleration is reached in the unilateral trial. It is possible that the patient must adjust AROM, velocity and acceleration of its dominant hand to the AROM, velocity and acceleration of the non-dominant hand in bimanual exercises in order to perform a symmetrical movement. The differences could be explained by various reasons. One reason could be that the dominant hand of the control is also restricted by the performance of the non-dominant hand in the bimanual exercises. Another possible explanation is that the subject already understands the exercise after having it performed three times bimanually and therefore performs better.

As expected, when comparing the affected arm to the non-dominant arm in the bimanual exercise, clear differences are seen in AROM for both pronation and supination. There is a more obvious difference for supination, as the patient does not even reach neutral position. Clear differences in the velocity, acceleration and smoothness values are seen as well. These differences can be explained by the spasticity in the patient's PT and a weakened supinator and BB, which are described in the patient's clinical assessment. When comparing these sides in the unimanual analytical trial, the same differences are seen. The velocity and acceleration reached with the non-dominant hand of the control are way higher than reached in the non-dominant hand of the patient.

In the symmetry indexes of the bimanual exercises a dominance of the dominant side is seen for all parameters in the patient. A dominance of the non-dominant hand is seen for all parameters, except for supination AROM and AROM range, in the control. This dominance of the non-dominant hand was not what was expected but the differences between the dominant and non-dominant hand are rather small. It can thus be a normal variation and mean that both sides perform equally.

When comparing the unimanual exercises to the bimanual exercises some differences appear. As expected the AROM parameters of the unaffected side of the patient are bigger in the unimanual exercise, this can be due to the fact that there is less restriction of movement by focusing too much on moving the affected side. This focus is eliminated in the unimanual exercise as the patient has the opportunity to only move his unaffected arm. For the same reason, the velocities of the dominant arm of the patient in the unimanual exercise were expected to be and are now proven to be higher. The AROM of the unaffected arm is, as expected, slightly smaller in the unimanual trials. An explanation can be that the coordination might be more difficult without the accompaniment of the dominant hand.

In this study, jerkiness was one of the evaluated parameters. It is defined as the area under the absolute acceleration curve. The comparison of the jerk scores between the patient and control shows a low jerk score for the affected hand of the patient. The unaffected hand of the patients and both hands of the control had a similar high area under the absolute acceleration curve. In this study it is seen that patients reach a lower acceleration, which is possibly due to poor selective motor control and co-contractions, leading to smaller areas under the absolute acceleration curve and thus lower ‘jerkiness’.

Calibration

As mentioned above, the angles in this study don’t match the clinical approach on the angles of pro- and supination. Calibration by using the triangular calibration device could solve this problem, but this hypothesis is not confirmed by the results. The difference in degrees measured between the pronated position on the table (90°) and 60° pronation using the 30° slope of the device should be 30°, however the displayed difference in AROM is smaller, varying between 17° and 23°. This shows these angles are subject to the position of the elbow during calibration, standardizing and securing the position of the elbow and the upper arm might improve these results. The elbow and upper arm position during calibration must be well defined to have a reliable outcome. Instead of using the calibration device, the angles measured by Nexus could be matched with the angles derived from the clinical assessment by the therapist. However, this is a subjective way to interpret these angles.

Functional trials

For the functional tasks, it seems that the chosen exercises were not too difficult for all subjects of all ages. Every subject seemed to understand the given instructions and executed the task correctly from the first try, according to their capabilities. Second tries were usually not necessary. The ping-pong exercise might have been the most difficult exercise, as holding the racket in the right way was not easy.

Ping-pong

As mentioned above, the start sign by revealing the marker in the 3D field is an event that can be easily marked in time, but the marker is not always revealed at the exact same time of the verbal signal. This makes it hard to determine the exact deadtime. The video recordings can be used to check this point in time with the movement of the mouth of the instructor. However saying “go” lasts longer than one timeframe so the assignment of this event to a certain timeframe is subject to the processer. It should be considered to have this point reviewed by different processers to cut the subjectivity to a minimum. Furthermore observers must be careful not to prepare the subject before the start of the exercise, for example by saying “ready, set, go” instead of “go”, as subjects will anticipate the movement which will decrease deadtime. In future studies the use of a switch with a beeper sound with voltage signal into the analogue data channels is recommended, to objectively and more easily judge the starting movement.

Another point of discussion is how to visually score the task as ‘successfully completed’ during the assessment, in order to avoid a failed trial and useless data. A way to assess this is to look at the alternation of the visible colour on the racket. A successful trial would then be if there is a clear alternation between the red and the blue side of the racket. The observer is held responsible to motivate the subject to go as fast as possible whilst keeping an eye on the AROM and motivating the subject to keep alternating colours. This approach seems like the easiest and fastest way to score the exercise during the assessment as graphs are not directly available during the assessment. A 2nd possible approach is to look at the graphs and set a cut-off AROM for supination-to-pronation cycles or look at the trajectory of the markers on the ping-pong bat. This cut-off value could be based on the AROM needed for normal functioning. This method necessitates the need to process part of the data during the assessment, in order to retrieve the needed graphs. This would extend the duration of the trial. In both of these approaches, CP patients might not be able to reach the cut-off, while really trying to fully pro- and supinate. Not reaching these cut-off values does not necessarily mean the exercise was not performed correctly, it could also be that the patient is unable to perform a sufficient AROM.

Results of the ping-pong trails

Between the dominant arms of both the patient and the control, no differences were seen in AROM and deadtime. However, the control achieved higher velocity and acceleration rates,

resulting in more completed cycles. When comparing the non-dominant sides, the control showed an obvious larger AROM, larger maximal reached angles, shorter deadtime, higher velocity and acceleration rates resulting in more than twice as many completed cycles than the patient. These results were as expected as spasticity is velocity dependent and because of the poor selective motor control known in children with cerebral palsy.

In the symmetry indexes a dominance of the dominant side was seen for AROM and velocity in both patient and control and for acceleration in the patient. The non-dominant side of the control reached slightly higher acceleration rates, completed more cycles and had a smaller deadtime than the dominant side, which can be due to normal variation and/or to the fact that control was 'trained' in this exercise after completing it on the dominant side. When comparing the number of completed cycles between patient and control, the control completed more cycles with both arms than the patient, which can be due to normal variation on the dominant sides. However the fact that the amount of completed cycles doesn't differ that much between the patient's arms can be misleading. As the AROM of the patient's affected side is much smaller than the range of his unaffected side, a lower velocity to complete the same amount of cycles is generated on the affected side. This clarifies that the range of motion as well as speed and in extension the acceleration must be kept in mind while interpreting the amount of completed cycles as it can reflect an inability in one or more of these parameters and not necessarily speed alone.

The angels reached in the static maximum pronation and supination trials, whilst holding the bat, were exceeded in the dynamic trials of the ping-pong exercise. This difference might be explained by the fact that it was very hard to explain to the subjects how to hold the racket and how to perform maximal angles. These results show that these trials must be improved. The relevance of these angles can also be put to discussion. As it is too hard to explain, subjects will not perform optimally, thus results will not reflect their actual ability and have no clinical significance.

Hand-to-head

Not being able to touch the head in supination might have important implications on the daily functional abilities of the patients as it can limit their capacity to eat, drink or dress independently. To be able to touch the forehead is a matter of shoulder function and elbow flexion, irrespective of forearm pro- or supination. Being able to touch the forehead in a supinated or pronated position includes the process of performing pro-and supination. It is assumed that subjects who are able to touch the forehead but unable to do this in supination have greater difficulties in daily life activities than subjects who can reach the forehead in supination.

When the forehead is touched in pronation, the obtained graph describing the rotation of the forearm is not a sinusoidal function. This makes it impossible to retrieve 4 supination-to-pronation cycles and thus to process the trials of subjects reaching their forehead in pronation. That's why in this study the exercise is only scored as successful when the forehead is reached with the forearm in supination as judged by the video footage. This means that success of the exercise is partly scored subjective, because looking only at the graphs gives no information about touching the forehead at the moment of full supination. When the forehead is covered by the hand, regardless its rotation, the marker that is applied on the forehead will disappear in the orthogonal view of all markers in Nexus as it is no longer visible for the cameras. Subjectivity is reduced to a minimum, by combining the video footage with the graphs and the disappearance of the marker to score if the subject touched the forehead in supination. Further reduction of subjectivity is achieved by the independent scoring of the exercises by 2 processers. A more objective method of scoring the exercise in the future could be to look at the AROM at the moment the hand touches the head, this moment is then defined as the moment where the speed of the arm approximates 0 rad/s. To estimate the subject's actual functional capacities, both the instructions and the demonstration of the exercise are done in supination. However the subject is not corrected if he or she performs the exercise in pronation. Not correcting the subject gives a good estimation of their real daily life capacities and, in addition, they will not feel like they failed the exercise or that they are not able to do this exercise, which reduces the risk of demotivation.

However this approach has one major downside. When success relies both on the supination and being able to touch the forehead, essential information regarding the patient's actual capacities gets lost when the patient is not encouraged to supinate. Therefore in the future, patients must be encouraged to touch the head in supination. This way the graphs and outcome data will be more representable of the patient's actual (in)capabilities. Not encouraging the patient to perform a supination may cause patients to choose the easy way of covering the marker, which is in pronation.

Results of the hand-to-head trails

The results of the patient and the control were similar when comparing the dominant sides. As expected, no obvious differences were seen in AROM and success. In the non-dominant arms, the maximal pronation angles were larger for the patient compared to the control. The maximal pronation angles were also larger than those measured in the analytical trials. This might be explained by the fact that the elbow is not supported by the armrests in this exercise and the patient can thus move his arm to obtain almost full contact with the table. When resting on the table, no muscle coordination or contraction is needed. The exercise was scored as unsuccessful for the non-dominant side of the patient and as successful for the control.

Because of the limited supination capacities, as judged by the AROM derived from the analytical trials where the mean range was 12°, and the failure to successfully complete this exercise, it is assumed this patient cannot reach his forehead in supination with great implications on his abilities in daily life activities.

The benefit of this quick exercise is that it is an easy way to estimate the subject's functionality in daily life activities. It is easy to repeat, to explain and to demonstrate and there is little need for materials.

Clapping

The clapping exercise was chosen to quantify the amount of compensation by the dominant arm, something the patient might be unaware of. This exercise demonstrates that the affected arm supinates less, but this is compensated by more supination on the unaffected side, which leads to a clap.

In this study, the clapping event and the returning to starting position are judged subjectively based on the video. An objective and probably better way to score the clapping and starting event would be to look at the shortest and largest distance between both RST markers and to look at the supination and pronation angles reached at these moments in time. One could look only at the elbow angles in the graph, but this gives no information about when and where both hands touch. The hands can reach the point of 0° pro- and supination before reaching the median plane of the body or before reaching the other hand. Moreover, the middle or the other hand can be reached before attaining 0° pro- and supination.

Possible hand positions were drawn on the table and every child was assigned the best fitting starting position. The clapping event was defined as the first frame in which both hands had the most contact and the starting position was defined when both hands were at shoulder width in the hands drawn at the table. Many subjects exceeded these starting positions, but this is mostly due to shoulder movement and thus only affects timing of the trial but not the AROM. The movement of the hand can also be described as the trajectory of the markers, which is an objective way to describe this exercise, and allows the measurement of the lateral to medial displacement of the arms at the time of the actual clapping.

As the clapping lasts longer than one timeframe, the processer has to decide in which frame the clapping takes place. In this study, the agreement was to label the first frame in which both hands had the most contact as a clapping event. As the subject doesn't really move its hands while clapping, the supination angles vary only slightly by just a few degrees. This minimalizes the difference in data between different processers and thus doesn't demand a review by other processers. The clapping event could also be defined as the moment when both hands reach zero velocity, as judged by the velocity graphs.

Results of the clapping trails

When comparing the unaffected side of the patient with the dominant side of the control, a difference in maximal reached pronation was seen. The control performed less supination than the patient, resulting in a smaller AROM. This can be explained by the fact that the patient has to compensate for the lack of rotation on his affected side. The larger value for the pronation peak seen in the unaffected hand of the patient can be caused by different arm and thus elbow positions in space. When comparing the affected side of the patient to the non-dominant side of the control, a larger supination peak was seen in the control. This is explained by the incapacity of the patient to perform a sufficient supination on his affected side. The differences in AROM were as expected, with a limited AROM for the patient due to spasticity and muscle weakness. All measurements of the distance to the midline resulted in positive values. This means that the clapping took place close to the midline and no hand crossed this midline, nor for the patient nor for its control. It was expected that the patient's dominant hand was going to cross the median axis. To really validate this hypothesis the data of the other subjects also needs to be quantified and scored. This exercise clearly shows the compensation of the dominant hand for the lack of rotation in the affected hand of the patient, however this compensation was not seen in the distance to the midline of clapping in this particular case.

MVC

Because these exercises can cause muscle fatigue, it is important to perform these at the end of the assessment. However, at the end of the protocol the subjects are already tired which could lead to a suboptimal performance. Especially the younger children were hard to motivate at this point of the protocol. Giving clear instructions to provoke the correct resisted movement is not easy, as patients often have limited selective motor control.

Processing

Revising the static trial after labelling is very important, as incorrect labelling affects all the other trials of one subject and leads to incorrect data. Two processers each processed several trials, but every subject was processed by the same processer. Only the ping-pong exercises of all subjects were done by the same processer, to make sure every trial was processed the same way and to reduce the effect of different processers on the variability of the results. The processing part of every assessment takes about 2 hours for every subject to be completed. Limiting the number of repetitions could limit the time needed for processing. The ping-pong exercise might be the only exercise that needs change, as the need for holding a racket is challenging in some subjects. An exercise that also focusses on speed is therefore suggested.

The 2 biggest problems that were encountered were the disappearance of the UST and FA2 markers during maximal supination before the ping-pong exercise and defining pro- and supination cycles in patients who had a severely affected upper limb. The problem of the

disappearing markers can be solved by starting the calibration from a neutral position to a maximal supination or pronation or performing a maximum pro- and supination in the same trial. This way, reconstruction of lost markers is more likely because they will have been captured at least once during this trial. The reconstruction of lost markers relies on the tracking of three other markers and on some frames in which all four markers are visible.

The start of movement in the ping-pong trials was defined as the small pronation-peak seen before attempting supination. There is not really an explanation for this phenomenon. It could perhaps be due to (antagonist) muscle contraction that may create an impression of joint motion. As it is seen in every subject, it can be noted that it is a preparation for movement and bracing of the joints to achieve the desired rotation.

Judging the timing of events in pro- and supination cycles in children who had difficulties supinating was much more difficult. At times a clear attempt to rotate was seen on the video footage and the graphs, but this attempt was not synchronous with the unaffected hand. In the graphs an alternation in the range was seen for both hands, however the range of motion reached in the affected hand was very small. This small range could also be explained by noise or movement of the subject. This can be explained by a lack of selective muscle activation and difficulties overcoming spastic pronator muscles. In this case, the graphs were the guideline to insert events.

Future

First work in the future will be to interpret all data gathered of the whole pool of subjects that participated in this assessment and to assess the hypotheses in all subjects.

In this study clinical information of previous doctor and physician appointments was used to compare with the results. In the future it is recommended to perform a clinical assessment before the start of the protocol. This to avoid big time gaps between gathering clinical information and information gathered from the protocol.

Initially the goal was to score mirror movement as a parameter as well. Due to a lack of time and an objective way to score this, this parameter was left out. It is suggested that this parameter is implemented in future assessments as it could provide information on the degree of neuroplasticity that has occurred. An objective way of quantifying mirror movement could be scoring it as present when the inactive hand reaches a certain percentage of its AROM reaching it synchronised with the active hand in an assessment. The unimanual analytical exercises given in this assessment are suitable to do so as both forearms are resting in a standardised, non-restricted position and AROM of both the non-active and active side is captured at the same time.

It should be revised on how to implement the calibration part. The elbows and upper arms of the subjects must be fixed whilst calibrating. This is necessary to gain an optimal clinical interpretation of the data.

A limitation of this study could be that movement of the trunk and the shoulder were not measured. Including these in the assessment could provide additional information on, for example, compensatory movements. Although this study included a variety of CP severities, the sample size was small and the focus was on unilateral CP. Including more subjects was impossible due to time restrictions. It is suggested future studies include more patients of all CP subtypes, to see if the results found in this study are seen in a larger population as well.

In future studies investigating pro- and supination in children with cerebral palsy, it is suggested to incorporate kinematic and EMG data, as they contribute to a quantitative and objective measurement. When implementing this protocol, further investigations are needed to limit the duration by reducing the number of repetitions. Interpretation of the EMG data, which was out of the scope of this study, could add more information on muscle coordination. At last future studies are necessary to check if therapeutic decisions can be made using the outcome of this protocol and if this protocol is sensitive enough to detect changes after treatment or interventions.

Conclusion

So far, CP classification systems tend to be subjective and do not incorporate any form of kinematics or EMG. This study incorporated these measurement techniques in order to objectively score the ability to pro- and supinate. 24 subjects have performed several analytical and functional tasks, which were captured in a kinematics system with simultaneous EMG registration. Clear differences between a patient with a severe type of CP and his age- and gender matched control were noted. By scoring movement in an objective way, the goal is to direct treatment and assist the clinician in making therapeutic decisions. Future studies are necessary to refine this work and to prove its use in the daily clinical setting.

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Attachments

Attachment 1: Alphabetical list of abbreviations

Acc.:	Acceleration
AHA:	Assisting Hand Assessment
Ang.:	Angular
AROM:	Active range of motion
BB:	Biceps Brachii
CIMT:	Constraint induced movement therapy
CP:	Cerebral palsy
EMG:	Electromyography
GABA:	γ-aminobutyric acid
GMFCS:	Gross Motor Functional Classification System
ISB:	International Society of Biomechanics
MACS:	Manual Ability Classification System
MHC:	Modified House Classification
MRC:	Medical Research Council
MUUL:	Melbourne Assessment of unilateral Upper Limb Function
MVC:	Maximal voluntary contraction
SCPE:	Surveillance of Cerebral Palsy in Europe
SD:	Standard deviation
Sup:	Supination
PQ:	Pronator Quadratus
Pron:	Pronation
PT:	Pronator Teres
Rad:	Radian
Vel:	Velocity

Attachment 2: House classification and MRC-scale

Table 1: House classification

House Class	Designation by House	Activity level according to House
0	Does not use	Does not use
1	Poor passive assist	Uses as stabilizing weight only
2	Fair passive assist	Can hold onto object placed in hand
3	Good passive assist	Can hold onto object and stabilize it for use by the other hand
4	Poor active assist	Can actively grasp object and hold it weakly
5	Fair active assist	Can actively grasp object and stabilize it well
6	Good active assist	Can actively grasp object and then manipulate it against other hand
7	Spontaneous use, partial	Can perform bimanual activities easily and occasionally uses the hand spontaneously
8	Spontaneous use, complete	Uses hand completely independently without reference to the other hand

Source: Hand Function in Cerebral Palsy. Report of 367 Children in a Population-Based Longitudinal Health Care Program, *Arner M et al* (17)

Table 3: Medical Research Council Scale for Muscle Strength

Scale	Effort
0	No movement
1	Fasciculations or small movement are observed
2	Movement only possible when resistance of gravity is removed
3	Movement against gravity possible, but not against resistance
4	Reduced strength, but movement against resistance is possible
5	Movement against full resistance is possible

Source: Aids to the examination of the peripheral nervous system. *Medical Research Coucil* (38)

Attachment 3: Informed consent for a child above the age of 12

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Informatie voor de minderjarige patiënt of vrijwilliger ouder dan 12 jaar:

Project:
Vergelijkend kinematisch en elektromyografisch onderzoek voor wat betreft de bovenste lidmaatfunctie bij kinderen met cerebraal parese versus een controlegroep van gezonde leeftijdsgenoten en volwassen vrijwilligers.

Beschrijving en doel van het project.

De dienst kinderorthopedie doet onderzoek naar de beste manieren om kinderen met hersenverlamming of cerebraal parese te behandelen. Veel kinderen met hersenverlamming kunnen één of beide armen moeilijker of niet gebruiken. Wij zoeken graag uit hoe dat precies komt.
We denken namelijk dat als we de oorzaken beter kennen, onze behandeling ook steeds beter wordt..

Wij vragen jouw toestemming voor het uitvoeren van enkele niet-pijnlijke tests terwijl jij een paar eenvoudige opdrachtjes uitvoert met je beide armen en handen. Deze opdrachtjes zijn heel simpel, het gaat bv om het draaien van je handen of het opheffen van een glas water.
Terwijl jij deze bewegingen maakt, meten wij via speciale sensoren die we op je huid kleven hoe actief je spieren zijn en hoe goed je de gewrichten in je arm kan bewegen. Deze gegevens kunnen we dan vergelijken met de resultaten van leeftijdsgenootjes met en zonder hersenverlamming en van volwassenen.

Als jij bij ons bent ingeschreven in het CP-centrum, maken deze tests deel uit van een gepland onderzoek van je armfunctie. Als je vrijwillig deelneemt wordt er ongeveer 2 uur van je tijd gevraagd.

Deze studie werd goedgekeurd door een onafhankelijke Commissie voor Medische Ethiek verbonden aan dit ziekenhuis, en zal worden uitgevoerd volgens de richtlijnen van ICH/GCP opgesteld in de verklaring van Helsinki opgesteld ter bescherming van individuen deelnemend aan klinische studies.

Voordelen
Je doet vrijwillig mee aan deze studie, dat betekent dat er geen enkel voordeel maar ook geen nadeel voor jezelf is verbonden aan je deelname maar de resultaten kunnen er wel voor zorgen dat we betere manieren vinden om kinderen met hersenverlamming te helpen.

Kosten
Deelnemen kost niets maar je kan er ook niets mee verdienen.

Vertrouwelijkheid
Als je wilt deelnemen aan de studie gebeurt dat helemaal anoniem. Dat betekent dat jouw naam en andere persoonlijke gegevens niet zullen worden gebruikt en dat de resultaten ook niet kunnen worden terug gevonden in jouw eigen medisch dossier. Ook als de resultaten van de studie worden gepubliceerd, is jouw anonimiteit verzekerd. Dat hoort zo volgens de Belgische wet van 8 december 1992 en de Belgische wet van 22 augustus 2002.

Verzekering:
Een andere wet, de 'experimentenwet' van 7/05/2004 zorgt ervoor dat elke deelnemer aan een wetenschappelijk project verzekerd moet zijn voor het risico (hoe klein of bijna onbestaand dat risico ook is) dat de deelnemer loopt. In het geval van onze studie is de kans dat je zou gekwetst geraken door mee te doen heel heel klein maar door de verzekering ben je in ieder geval beschermd in het zeldzame geval dat dit toch gebeurt.

Toestemmingsverklaring

Jouw Naam en Voornaam .....

Adres.....

Geeft toestemming tot deelname aan het wetenschappelijk onderzoek.

Ik heb genoeg uitleg gekregen om goed te begrijpen waar de studie over gaat en wat er precies van mijn deelname verwacht wordt. Als ik wil kan ik steeds om meer uitleg vragen aan de begeleiders.

Ik weet dat deze studie op voorhand werd goedgekeurd door het Ethisch Comité van het UZ Gent.

.

Ik weet dat ik op elk moment kan zeggen dat ik niet meer wil deelnemen, zonder dat ik hiervoor een reden moet geven. Als ik niet meer wil deelnemen heeft dit geen invloed op mijn behandeling of op mijn verhouding met de dokter of andere medewerkers.

Gelezen en goedgekeurd, Datum:.....

Dr. S. Lauwagie

.....

(Stempel en handtekening) (Naam en handtekening)

FACULTY OF MEDICINE AND HEALTH SCIENCES

Attachment 4: Informed consent for a child younger than 12 years old

bewegingsstelsel

Universitair Ziekenhuis Gent

UNIVERSITEIT GENT

KLINIEK VOOR ORTHOPEDIE EN TRAUMATOLOGIE

Diensthoofd
Prof. dr. J. Victor

Hand- en Microchirurgie
Prof. dr. N. Hollevoet
Dr. W. Vanhove
Dr. A. Vanden Berghe (consulent)

Heup
Prof. dr. C. Pattyn
Dr. E. Audenaert

Kind en scoliose Prof. dr. F. Plasschaert Dr. S. Lauwagie

Knie
Prof. dr. J. Victor
Dr. N. Arnout

Plexus brachialis
Dr. W. Vanhove

Elleboogchirurgie
Dr. W. Vanhove
Dr. A. Van Tongel

Schouder en elleboog
Prof. dr. L. De Wilde
Dr. A. Van Tongel
Dr. A. Karelse (consulent)

Traumatologie
Bovenste lidmaat:
Dr. A. Van Tongel
Wervelkolom:
Prof. Dr. B. Poffyn
Dr. G. Sys
Bekken:
Dr. E. Audenaert
Prof. dr. C. Pattyn
Onderste lidmaat:
Dr. E. Audenaert

Dr. A. Ringburg (consulent)

Tumoren (bot en weke delen)
Prof. Dr. B. Poffyn
Dr. G. Sys

Voet en enkel
Dr. W. Bongaerts
Dr. B. Devos Bevernage (consulent)

Wervelkolom
Prof. Dr. B. Poffyn
Dr. G. Sys
Dr. K. Hendrix (consulent)
Dr. K. Van der Donckt (consulent)
Dr. K. Verheye (consulent)

Cerebral Palsy Referentiecentrum
Labo voor Bewegingsanalyse
Prof. dr. F. Plasschaert
Prof. dr. ir. M. Forward

Klinische research
Dr. C. Van Der Straeten

Informatie voor de patiënt of de ouder/voogd van de minderjarige patiënt (<12 jaar):

Project:
Vergelijkend kinematisch en elektromyografisch onderzoek voor wat betreft de bovenste lidmaatfunctie bij kinderen met cerebraal parese versus een controlegroep van gezonde leeftijdsgenoten en volwassen vrijwilligers.

Beschrijving en doel van het project.

De dienst kinderorthopedie/CPRC voert een onderzoek uit naar het voorkomen van beperkingen in bovenste lidmaatfunctie bij kinderen met hersenverlamming. Dit om in de toekomst onze diagnostische en behandelingsstrategieën te kunnen oppuntstellen.

Wij vragen uw toestemming voor het uitvoeren van enkele niet-invasieve en niet-pijnlijke tests bij u of bij uw kind. Het betreft het uitvoeren van een aantal simpele, dagdagelijkse handelingen met de beide armen waarbij we via oppervlakkige kleefsensoren de activiteit in de verschillende spiergroepen van beide armen meten. We registreren, eveneens via oppervlakkige, klevende markers, de bewegingen die de armen maken in 3D. Deze gegevens worden vergeleken tussen de patiëntengroep en de vrijwilligersgroep.

Voor de patiëntengroep maken deze tests deel uit van een gepland onderzoek van de bovenste lidmaatfunctie. Aan de controlegroep wordt hun vrijwillige medewerking gevraagd.

Deze studie werd goedgekeurd door een onafhankelijke Commissie voor Medische Ethiek verbonden aan dit ziekenhuis, en zal worden uitgevoerd volgens de richtlijnen van ICH/GCP opgesteld in de verklaring van Helsinki opgesteld ter bescherming van individuen deelnemend aan klinische studies.

Toestemming en weigering
Het staat u volkomen vrij om toe te stemmen of te weigeren in de deelname van u/uw kind.
U kunt weigeren zonder dat u hiervoor een reden moet opgeven en zonder dat dit op enigerlei wijze een invloed zal hebben op uw verdere behandeling en/of de relatie met de behandelende artsen. Als u toestemt, wordt u gevraagd het toestemmingsformulier te tekenen.

Voordelen
Deze studie biedt geen medisch of ander voordeel voor uzelf of voor uw kind, maar de bekomen resultaten kunnen leiden tot nieuwe en meer efficiënte methodes voor de behandeling van hand- en bovenste lidmaatproblemen bij kinderen met hersenverlamming.

Kosten
De deelname van u of uw kind aan de studie brengt geen bijkomende kosten met zich mee, maar biedt ook geen financieel voordeel.

Vertrouwelijkheid
Als u akkoord gaat om uzelf of uw kind aan deze studie deel te laten nemen, zullen uw/zijn/haar persoonlijke en klinische gegevens tijdens deze studie worden geanonimiseerd (hierbij is er totaal geen terugkoppeling meer mogelijk naar uw/zijn/haar persoonlijke dossier). In overeenstemming met de Belgische wet van 8 december 1992 en de Belgische wet van 22 augustus 2002, zal de persoonlijke levenssfeer worden gerespecteerd. Als de resultaten van de studie worden gepubliceerd, zal anonimiteit aldus verzekerd zijn.

Versie 1 – 23/09/2016

Verzekering:

De experimentenwet van 7/05/2004 verplicht ons om deelnemers aan wetenschappelijke projecten te verzekeren voor de deelname en het risico (hoe klein ook) dat men loopt.
De waarschijnlijkheid dat u door deelname aan deze studie enige schade ondervindt, is extreem laag. Indien dit toch zou voorkomen, wat echter zeer zeldzaam is, werd er een verzekering afgesloten conform de Belgische wet van 7 mei 2004, die deze mogelijkheid dekt.

Toestemmingsverklaring

Mevrouw/De Heer .....

(indien van toepassing) ouder/voogd van .....

Adres..... .....

(indien van toepassing) Stemt erin toe (naam) ..... deel te laten nemen aan het wetenschappelijk onderzoek.

Ik verklaar hierbij op een voor mij begrijpelijke wijze mondeling en schriftelijk te zijn ingelicht over de aard, de methode en het doel van deze studies.

Ik ben er mij van bewust dat dit project ter beoordeling en controle aan het Ethisch Comité van het UZ Gent werd voorgelegd en ik deze goedkeuring niet moet beschouwen als een motivatie tot deelname aan deze studie.

Ik ben ervan op de hoogte dat mijn deelname/ de deelname van mijn kind aan deze studies geen bijkomende kosten meebrengen en dat er geen financieel voordeel aan verbonden is.

De patiënt kan zich op elk moment terugtrekken tot op het ogenblik dat de gegevens in de database worden bewaard, zonder hiervoor een verklaring te hoeven afleggen en zonder dat dit op enigerlei wijze invloed zal hebben op de verdere behandeling en de relatie met de arts.

Gelezen en goedgekeurd,

Dr. S. Lauwagie

(Stempel en handtekening)

Datum:…….

Naam volwassen deelnemer / ouder of voogd

.....

(Naam en handtekening)

Attachment 5: Approval of the Ethics Committee

Universitair Ziekenhuis Gent

UNIVERSITEIT GENT

Afz: Commissie voor Medische Ethiek

COMMISSIE VOOR MEDISCHE ETHIEK

Poli Orthopedie
Dr. Sophie LAUWAGIE
ALHIER

Voorzitter:
Prof. Dr. D. Matthys
Secretaris:
Prof. Dr. J. Decruyenaere

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UW KENMERK	**ONS KENMERK**	**DATUM**	**KOPIE**
	2016/1102	10-feb-17	Zie "CC"

BETREFT

Advies voor monocentrische studie met als titel:
Vergelijkend kinematisch en elektromyografisch onderzoek voor wat betreft de bovenste lidmaadfunctie bij kinderen met cerebraal parese versus een controlegroep van gezonde leeftijdsgenoten en volwassen vrijwilligers.

Belgisch Registratienummer: B670201629619

* Adviesaanvraagformulier dd. 23/09/2016 (volledig ontvangen dd.26/09/2016)
* Begeleidende brief dd. 23/09/2016
* (Patiënten)informatie- en toestemmingsformulier
  - voor de meerderjarige patïent/deelnemer of de voogd/ouder van de minderjarige (versie 1.0 dd.23/09/2016)
  - voor de minderjarige patïent/deelnemer ouder dan 12 jaar (versie 1.0 dd.23/09/2016)
* Antwoord onderzoeker dd. 7/02/2017 op opmerkingen EC dd. 19/10/2016

Advies werd gevraagd door:
Dr. S. LAUWAGIE ; Hoofdonderzoeker

BOVENVERMELDE DOCUMENTEN WERDEN DOOR HET ETHISCH COMITÉ BEOORDEELD.
ER WERD EEN POSITIEF ADVIES GEGEVEN OVER DIT PROTOCOL OP 7/02/2017. INDIEN DE STUDIE NIET WORDT OPGESTART VOOR 7/02/2018, VERVALT HET ADVIES EN MOET HET PROJECT TERUG INGEDIEND WORDEN.
Vooraleer het onderzoek te starten dient contact te worden genomen met Bimetra Clinics (09/332 05 00).

THE ABOVE MENTIONED DOCUMENTS HAVE BEEN REVIEWED BY THE ETHICS COMMITTEE.
A POSITIVE ADVICE WAS GIVEN FOR THIS PROTOCOL ON 7/02/2017. IN CASE THIS STUDY IS NOT STARTED BY 7/02/2018, THIS ADVICE WILL BE NO LONGER VALID AND THE PROJECT MUST BE RESUBMITTED.
Before initiating the study, please contact Bimetra Clinics (09/332 05 00).

DIT ADVIES WORDT OPGENOMEN IN HET VERSLAG VAN DE VERGADERING VAN HET ETHISCH COMITE VAN 21/02/2017
THIS ADVICE WILL APPEAR IN THE PROCEEDINGS OF THE MEETING OF THE ETHICS COMMITTEE OF 21/02/2017

- *Het Ethisch Comité werkt volgens 'ICH Good Clinical Practice' - regels*
- *Het Ethisch Comité beklemtoont dat een gunstig advies niet betekent dat het Comité de verantwoordelijkheid voor het onderzoek op zich neemt. Bovendien dient U er over te waken dat Uw mening als betrokken onderzoeker wordt weergegeven in publicaties, rapporten voor de overheid enz., die het resultaat zijn van dit onderzoek.*
- *In het kader van 'Good Clinical Practice' moet de mogelijkheid bestaan dat het farmaceutisch bedrijf en de autoriteiten inzage krijgen van de originele data. In dit verband dienen de onderzoekers erover te waken dat dit gebeurt zonder schending van de privacy van de proefpersonen.*
- *Het Ethisch Comité benadrukt dat het de promotor is die garant dient te staan voor de conformiteit van de anderstalige informatie- en toestemmingsformulieren met de nederlandstalige documenten.*
- *Geen enkele onderzoeker betrokken bij deze studie is lid van het Ethisch Comité.*
- *Alle leden van het Ethisch Comité hebben dit project beoordeeld. (De ledenlijst is bijgevoegd)*

Universitair Ziekenhuis Gent
De Pintelaan 185,B- 9000 Gent
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Wendy Van de Velde
09/332 56 13
wendy.vandevelde@uzgent.be

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Attachment 6: Tables of the parameters and the results

Table 4: Overview analytical parameters

Parameter	Measurements	L/R
AROM pronation	Maximum pronation In degrees	Symmetry index (Non-dom/dom)
AROM supination	Maximum supination In degrees	Symmetry index (Non-dom/dom)
Supination over pronation index	(max. sup)/(-(max. pron)	Symmerty index (Non-dom/dom)
AROM	Mean active range of motion of 9 cycles, SD In degrees	Symmetry index (Non-dom/dom)
Average peak angular velocity pronation	Average peak angular velocity of 9 cycles, SD In rad per second	Symmetry index (Non-dom/dom)
Average peak angular velocity supination	Average peak angular velocity of 9 cycles, SD In rad per second	Symmetry index (Non-dom/dom)
Supination over pronation index	(average peak ang. vel. sup)/(-(average peak ang. vel. pron)	Symmerty index (Non-dom/dom)
Average peak angular accerleration pronation	Average peak angular acceleration of 9 cycles, SD In rad per second per second	Symmerty index (Non-dom/dom)
Average peak angular acceleration supination	Average peak angular acceleration of 9 cycles, SD In rad per second per second	Symmerty index (Non-dom/dom)
Supination over pronation index	(average peak ang. acc. sup)/(-(average peak acc. pron)	Symmerty index (Non-dom/dom)
Jerk	Area under the acceleration curve, SD	Symmetry index (Non-dom/dom)

Table 5: Overview of the parameters of the ping-pong exercise

Parameter	Measurements	L/R
AROM pronation	Maximum pronation In degrees	Symmetry index (Non-dom/dom)
AROM supination	Maximum supination In degrees	Symmetry index (Non-dom/dom)
AROM	Mean active range of motion, SD In degrees	Symmetry index (Non-dom/dom)
Mean angular velocity pronation	Mean angular velocity for pronation, SD	Symmetry index (Non-dom/dom)

	In rad per second	
Mean angular velocity supination	Mean angular velocity for supination, SD In rad per second	Symmetry index (Non-dom/dom)
Average peak angular acceleration pronation	Average peak angular acceleration for pronation, SD In rad per second per second	Symmetry index (Non-dom/dom)
Average peak angular acceleration supination	Average peak angular acceleration for supination, SD In rad per second per second	Symmetry index (Non-dom/dom)
Number of completed cycles	Mean # completed cycles	Symmetry index (Non-dom/dom)
Deadtime	Mean time In ms	Symmetry index (Non-dom/dom)

Table 6: Overview of the parameters of the hand-to-head exercise

Parameter	**Measurements**	**L/R**
AROM pronation	Maximum pronation In degrees	Symmetry index (Non-dom/dom)
AROM supination	Maximum supination In degrees	Symmetry index (Non-dom/dom)
AROM	Mean active range of motion, SD In degrees	Symmetry index (Non-dom/dom)
Success	Yes or no	No symmetry index

Table 7: Overview of the parameters of the clapping exercise

Parameter	**Measurements**	**L/R**
AROM pronation	Maximum pronation In degrees	Symmetry index (Non-dom/dom)
AROM supination	Maximum supination In degrees	Symmetry index (Non-dom/dom)
AROM	Mean active range of motion, SD In degrees	Symmetry index (Non-dom/dom)
Move to midline	Movement of the wrist markers relative to the shoulder markers In mm	Symmetry index (L and R separately)

Table 8: Results of the bilateral analytical exercises

	Patient *Dominant side*	*Affected side*	**Control** *Dominant side*	*Non-dominant side*
AROM Pronation				
Max (°)	62.0	55.1	74.9	76.7
Symmetry	0.89		1.02	
AROM Supination				
Max (°)	-61.3	25.8	-70.0	-60.6
Symmetry	-0.42		0.87	
Supination over pronation index				
(Max sup)/(-(max pron)	0.99	-0.47	0.94	0.79
symmetry	-0.47		0.84	
AROM range				
Mean range (°)	112.2	12.4	133.9	129.1
SD (°)	4.3	3.7	8.1	6.1
Symmetry	0.11		0.96	
Velocity Pronation				
Average peak (rad/s)	3.6	0.2	4.5	4.8
SD (rad/s)	0.7	0.1	0.7	0.6
Symmetry	0.06		1.07	
Velocity Supination				
Average peak (rad/s)	-2.7	-0.2	-3.9	-4.6
SD (rad/s)	0.4	0.1	1.0	0.8
Symmetry	0.07		1.18	
Supination over pronation index				
(average peak vel. sup)/(-(average peak vel. pron)	0.75	1.00	0.87	0.96
symmetry	1.33		1.11	
Acceleration Pronation				
Average peak (rad/s/s)	11.5	0.5	17.5	19.7
SD (rad/s/s)	3.4	0.2	4.6	3.8
Symmetry	0.04		1.13	
Acceleration Supination				
Average peak (rad/s/s)	-10.5	-0.5	-15.0	-18.1
SD (rad/s/s)	3.3	0.2	4.4	4.4
Symmetry	0.05		1.21	
Supination over pronation index				
(average peak acc. sup)/(-(average peak acc. pron)	0.91	1.00	0.86	0.92
symmetry	1.10		1.07	
Jerk				
Mean Jerk	222.9	15.8	287.5	315.9
SD	40.6	7	68.8	73.8
Symmetry	0.07		1.09	

Table 9: Results of the unilateral analytical exercises

	Patient *Dominant side*	*Affected side*	**Control** *Dominant side*	*Non-dominant side*
AROM Pronation				
Max (°)	65.6	53.6	69.5	78.1
Symmetry	0.82		1.12	
AROM Supination				
Max (°)	-64.2	32.8	-78.0	-62.6
Symmetry	-0.51		0.80	
Supination over pronation index				
(Max sup)/(-(max pron)	0.98	-0.61	1.12	0.80
Symmetry	-0.62		0.71	
AROM range				
Mean range (°)	121.3	12.4	137.2	128.7
SD (°)	5.8	2.6	5.8	5.7
Symmetry	0.11		0.94	
Velocity Pronation				
Average peak (rad/s)	4.6	0.2	5.5	5.9
SD (rad/s)	0.6	0.1	1.0	0.8
Symmetry	0.04		1.07	
Velocity Supination				
Average peak (rad/s)	-4.2	-0.2	-5.0	-6.4
SD (rad/s)	0.6	0.1	0.3	1.6
Symmetry	0.05		1.28	
Supination over pronation index				
(average peak vel. sup)/(-(average peak vel. pron)	0.91	1.00	0.91	1.09
Symmetry	1.10		1.20	
Acceleration Pronation				
Average peak (rad/s/s)	16.5	0.5	24.4	34.8
SD (rad/s/s)	3.4	0.1	7.1	8.4
Symmetry	0.03		1.43	
Acceleration Supination				
Average peak (rad/s/s)	-15.5	-0.4	-21.0	-33.1
SD (rad/s/s)	3.7	0.1	4.0	11.3
Symmetry	0.03		1.58	
Supination over pronation index				
(average peak acc. sup)/(-(average peak acc. pron)	0.94	0.80	0.86	0.95
Symmetry	0.85		1.11	
Jerk				
Mean Jerk	424.6	21.7	395.0	573.4
SD	126.7	5.8	91.3	120.8
Symmetry	0.05		1.45	

Table 10: Reference angles

	Patient		Control	
	Dominant side	Affected side	Dominant side	Non-dominant side
Calibration 90° pronation	45.7° SD 0.6°	47.5° SD 1.3°	46.5° SD 0.9°	48.8° SD 1.1°
Calibration 60° pronation	25.2° SD 1.1°	29.3° SD 0.3°	29.8° SD 0.3°	26.2° SD 0.6°
Calibration range	20.5°	18.2°	16.7°	22.6°
Ping-pong max pronation	37.2°	56.6°	53.0°	34.6°
Ping-pong max supination	ERROR	46.0°	-73.8°	-28.4°

Table 11: Results of the ping-pong exercises

	Patient		**Control**	
	Dominant side	*Affected side*	*Dominant side*	*Non-dominant side*
AROM Pronation				
Max (°)	90.0	53.1	86.3	77.5
Symmetry	0.59		0.90	
AROM Supination				
Max (°)	-77.1	43.7	-77.5	-75.6
Symmetry	-0.57		0.98	
AROM range				
Mean range (°)	142.1	3.0	134.3	118.7
SD (°)	11.5	2.3	29.7	15.8
Symmetry	0.02		0.88	
Velocity Pronation				
Mean ang. vel. (rad/s)	8.5	0.1	9.7	9.1
SD (rad/s)	0.7	0.0	2.6	1.4
Symmetry	0.01		0.94	
Velocity Supination				
Mean ang. vel.(rad/s)	-8.9	0.0	-10.2	-9.6
SD (rad/s)	1.1	0.0	2.5	1.6
Symmetry	0.00		0.94	
Acceleration Pronation				
Average peak (rad/s/s)	153.1	0.2	197.1	202.7
SD (rad/s/s)	28.2	0.4	42.1	43.5
Symmetry	0.00		1.03	
Acceleration Supination				
Average peak (rad/s/s)	-144.0	-0.2	-242.2	-253.3
SD (rad/s/s)	23.6	0.3	45.1	47.3
Symmetry	0.00		1.05	
# Completed cycles				
Mean #	5.3	4	8.3	9.3
Symmetry	0.76		1.12	
Deadtime				
Time (ms)	40.0	45.3	40.3	35
Symmetry	1.13		0.87	

Table 12: Results of the hand-to-head exercises

	Patient		**Control**	
	Dominant side	*Affected side*	*Dominant side*	*Non-dominant side*
AROM Pronation				
Max (°)	55.4	94.9	63.1	62.1
Symmetry	1.71		0.98	
AROM Supination				
Max (°)	-68.4	35.5	-62.2	-43.7
Symmetry	-0.52		0.70	
AROM range				
Mean range (°)	113.7	40.4	104.8	91.8
SD (°)	3.8	14.9	8.1	6.7
Symmetry	0.36		0.88	
Success				
Yes/No	Yes	No	Yes	Yes

Table 13: Results of the clapping exercises

	Patient		**Control**	
	Dominant side	*Affected side*	*Dominant side*	*Non-dominant side*
AROM Pronation				
Max (°)	80.5	48.4	56.6	51.0
Symmetry	0.60		0.90	
AROM Supination				
Max (°)	-47.2	29.4	-36.9	-40.4
Symmetry	-0.62		1.09	
AROM range				
Mean range (°)	83.6	9.4	74.3	67.4
SD (°)	10.9	4.4	6.8	7.5
Symmetry	0.11		0.91	
Distance to the midline				
Mean distance (mm)	97.3	35.6	20.3	54.9
SD	33.0	22.6	13.1	15.8
Symmetry	0.37		2.70	