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Validity of computer-based video analysis for the assessment of postural control in individuals with cerebral palsy

Graduate thesis in Medicine
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Trondheim, January 2017

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NTNU
Kunnskap for en bedre verden

Innholdsfortegnelse

Acknowledgements

I would like to express my gratitude to all those who have helped me during the process of fulfilling this thesis. First and foremost I would like to thank my main supervisor, Professor Torstein Vik, for his encouragement, guidance and patience, and for teaching me the principles of research and academic writing. My co-supervisors, Lars Adde (PhD) and Rannei Sæther (PhD), also deserve great thanks for their incredible involvement. Thank you for always having an open door and for putting so much work into supervising me. I would also like to thank my colleague, medical student Mali Kanstad, for great co-operation during the entire process, for her patience with me and for all the work we have put in together. Finally, I would thank Alexander Jensenius for helping with the software and for adapting our data for the analyses.

ABSTRACT

BACKGROUND: Many studies show that individuals with cerebral palsy (CP) have problems with postural control, which is important for the ability to carry out day-to-day activities and tasks. However, there is no common agreement on how balance and postural control should be assessed in a regular clinical setting in individuals with CP. This makes evaluation of different interventions to improve postural control difficult.

AIM: This study investigated whether computer-based video analysis could be used to quantify postural control.

METHOD: The participants of this study, thirteen individuals with CP, and 24 typically developing (TD) individuals were instructed to intend to stand still while they were video-recorded. The movements made during the video recordings were quantified using computer-based video analysis. After the recordings, the participants with CP performed the Gross Motor Function Measure, Item set 66 (GMFM-66 Item set). Face validity was examined by comparing the quantification from the computer-based video analysis with observations from the video recordings. Construct validity was examined by calculating the correlation between the variables from the computer-based video analysis and the scores from GMFM-66 Item set, and by comparing the scores of the computer-based video analysis between individuals with CP and TD individuals.

RESULTS: In the first part of this study we found that the mean and standard deviation of one variable, the centroid of motion in the horizontal axis, correlated best with postural control assessed with GMFM-66 Item set. One variable, the quantity of motion had moderate to good correlations, but was too sensitive to confounders such as clothing and was therefore excluded from further analyses. The correlation coefficients with other variables from the computer-based video analysis were low, and we chose to exclude them as well. In the second part of the study, observations of body movements on the video recordings coincided with the quantification of the centroid of motion, consistent with face validity. Moderate to good correlations were found between the mean values of the centroid of motion and GMFM-66 Item set dimension D (Pearson correlation coefficient ranging from 0.68-0.76, $p < 0.05$). The difference between groups was significant for the centroid of motion in the horizontal axis for all video recordings when split into individuals with CP and TD individuals. For one variable, the mean value of the centroid of motion, we found increasing mean values with increasing gross motor impairment (GMFCS level).

CONCLUSION: In this study I have found that one variable, the centroid of motion in the horizontal axis, calculated by a computer-based video analysis software may be used to asses postural control during quiet stance in individuals with CP. Two other variables may have the potential to describe postural sway, but future studies are needed to document this.

Abbreviations

APA = anticipatory postural adjustment

BHC = Beitostølen Healthsports Centre

BoNT = botulinum toxin

BOS = base of support

COM = centre of mass

COP = centre of pressure

COSMIN = consensus-based standards for selection of health measurement instruments

CP = cerebral palsy

Cx_{mean} = mean value for the spatial centre of motion in the horisontal axis

Cx_{SD} = variability (standard deviation) of the spatial centre of motion in the horisontal axis

GMFM = Gross motor function measure

GMFM-66 Item set = Gross Motor Function Measure, Item set 66

GMFCS = Gross Motor Function Classification System

IVH = intraventricular haemorrhage

MACS = Manual Ability Classification System

PHI = periventricular haemorrhagic infarction

PVL = periventricular leukomalacia

Q_{mean} = mean value for the quantity of motion: total amount of motion.

RPA = reactive postural adjustment

SCPE = Surveillance of Cerebral Palsy in Europe

TD = individuals without CP (typically developed individuals)

1. Background

1.1 Cerebral palsy

Cerebral palsy (CP) is a term that describes a group of permanent and non-progressive movement- and *posture* disorders, caused by a disturbance (lesions) in the brain during the early stages of human development, which is before two years of age.[1-4] The lesions in the immature brain that cause CP take place in the pre-, peri- or a postnatal period.[1] These disturbances of movement and posture will thus cause limitations in activity.[1,3] Persons with CP also have other limitations in addition to problems with movement and posture, such as problems regarding eating and digestion, vision and hearing abilities, cognition, perception, communication and behaviour.[1,3,5] A significant proportion also have epilepsy and secondary musculoskeletal problems, such as contractures, dislocations and joint deformities. [3,5]

CP is not a specific disease, rather an umbrella term, and the clinical findings depend on type and severity of the lesions in the brain.[6] Thus, CP is a clinical diagnosis where the different symptoms, both motoric and sensory, define the type and severity of the CP diagnosis, and the clinical picture will often change as the brain matures. [5,7] Some characteristic symptoms however, are spasticity, impairment of movement and motor control, muscle fatigue, ataxia and rigidity. [5,6]

Cerebral palsy is the largest diagnostic group treated in paediatric rehabilitation [4,8], and the prevalence in Norway is 2.5 per 1000 live births. [9]

Cerebral palsy is a clinical diagnosis. Neither laboratory test nor tissue histology can decide the presence or absence of CP. Magnetic resonance imaging (MRI) however, can be helpful in the process of making the diagnosis, as it can show where the lesions are situated (the timing of the injury) and help establish the pattern of disabilities.[10] During the history and clinical examination of a child with suspected CP, it is important to include details concerning gestational age, pre- and perinatal events and how the motoric milestones have been reached so far, as a delay in these are commonly seen in children with CP.[5] Unfortunately it is difficult to diagnose CP, and the median age at diagnosis is at present 18 months[1], since many of the symptoms can be difficult to discover before the child starts to have specific movements in the arms and legs. This normally occurs around 6 to 8 months of age.[1,10] In mild versions of CP symptoms can be very difficult to detect, and some children will not have an established diagnosis before the child's fifth birthday.[10]

1.1.1 Pathophysiology

The pathophysiology of CP depends on the timing of injury[11], during the pre-, peri- or postnatal period.[12]

For children born *preterm*, before 32 weeks of gestation, the most common pathophysiology is periventricular lesions, more specific: periventricular leukomalacia (PVL) and complications after intraventricular haemorrhage (IVH).[12] Ischemic events occurring between 34 and 40 weeks of gestation will most often lead to focal and/or multifactorial brain injuries.[10]

Intraventricular haemorrhage and periventricular haemorrhagic infarction

Preterm babies have a temporary structure near the lateral ventricles, the germinal matrix, that will regress before term. The germinal matrix is highly vascularized, and it is from this structure that the cells emerge during the maturing of the brain. The many capillaries of the germinal matrix are very fragile and can easily burst, and thus cause a haemorrhage during e.g. high ICP or a hypoxic event. An intraventricular haemorrhage (IVH) and possible periventricular haemorrhagic infarction (PHI) will occur in this area. A PHI is a haemorrhagic necrosis of the periventricular white matter that most often occur in association with a large IVH.[12,13] It seems that a PHI that appears in association with an IVH, is actually a venous infarction.[13] IVH and a possible PHI are most often seen the first days of extrauterine life in very preterm children. Since this event not necessarily happens bilaterally (67% of lesions reported are unilateral[13]), it is a common cause of spastic hemiplegia, that will be further explained later (under *classification*).

The severity of an IVH is graded as follows:[12]

I Haemorrhage in the germinal matrix
II Haemorrhage to the ventricles
III Haemorrhage, through to the ventricles that causes hydrocephalus.
IV With parenchymal haemorrhage

Periventricular leukomalacia

Periventricular leucomalacia (PVL) is a brain injury situated adjacent to the ventricles in the cerebrum and is normally caused by a hypoxic/ischemic event or a peri-/prenatal infection that leads to bilateral white matter necrosis.[12,13] This is the most common reason for the development of CP in children born preterm[10] and occurs because of injury to oligodendrocytes caused by ischemia in the developing cerebrum.[5] The ischemia occurs in the border zone at the end of arterial vascular distribution. Structures situated in this area, near the ventricles, such as the centrum semiovale and acoustic and optic radiations, are therefore particularly vulnerable regarding low perfusion. These structures will be affected if the preterm child suffers from an episode of anoxia/hypoxia because of low blood pressure or compromised systemic circulation. Another cause for small episodes of hypoxia and thus another cause of PVL, are infections, pre- or postnatal.[13] Naturally, both sides of the brain will be affected equally, and PVL is therefore especially associated with spastic CP. Since radiations from the pyramidal tract most commonly are affected, PVL is highly associated with affection of the lower extremities.[10] The first event will be ischemia, which may develop into necrosis (leucomalacia) and later cystic formations in the affected areas. In the most severe forms, this can result in the pattern of multicystic encephalomalacia.[12,13] In late MRI this can be seen as an enlargement of the ventricles, often accompanied by gliosis.[10,12,13]

Pathophysiology of CP in children born at term

For children born at term, the most common reasons for CP are congenital anomalies, infarction in the middle cerebral artery and perinatal asphyxia, possibly followed by encephalopathy, caused by e.g. maternal infections or respiratory failure.[10,12] An infarction in the middle cerebral artery is the most important reason for unilateral spastic CP in term or near term born children. This infarction in the middle cerebral artery may appear prenatal or in the neonatal period and is often caused by embolization from the placenta.[13] In this case the upper extremities are more affected than the lower extremities.[14] Another cause; perinatal asphyxia, may be caused by e.g. uterine rupture, cord prolapse or major placental abruption, and leads to a global hypoxia in the brain that will most often cause dyskinetic CP or spastic quadriplegic CP.[12]

1.1.2 Risk factors

The risk factors for CP are multiple, and most often several risk factors synergize and make disturbances in the immature brain and further development of CP more likely.[10,15] The most common reasons that lead to CP are circulation deficits in the cerebrum, haemorrhage, anoxia, infarctions and infections. Some of the conditions and situations that may predispose for lesions and further development of CP are intrauterine growth restriction, preterm birth, antepartum haemorrhage, coagulation disorders, multiple pregnancies, chromosomal anomalies, selected polymorphisms, intrauterine infections and many other conditions affecting either the mother or child.[5,7,10]

1.1.3 Classification

The classification of cerebral palsy can be assessed in many different ways. Some classifications are based on the clinical presentation of the symptoms, whilst other classifications, like the Gross Motor Functioning Classification (GMFCS) and the Manual Ability Classification system (MACS), focus on motoric abilities and function. These classification systems are meant to be used both in a clinical setting, and to differentiate individuals with the CP diagnosis for research purposes.[1] However, to this date, none of the proposals for classifications systems are fully able to capture the multifactorial clinical expressions of CP.[16]

Classification based on clinical presentation

The Surveillance of Cerebral Palsy in Europe (SCPE) has agreed upon a definition of CP that depend less on individual judgement.[4] This is the currently most used classification system in Europe, and is based on the neurological presentation of symptoms and thus the presumed neuropathological site of the lesion.[4,7]

In line with these guidelines, CP is divided into different subgroups according to the neurological symptoms presented. The subgroups presented are: spastic (82%), dyskinetic (6%) and ataxic (5%), based on the neurological symptoms that dominate.[4,7] The spastic subtype is further divided into a bilateral (limbs on both side of the body is affected) and a unilateral type (limbs on one side of the body is affected). The unilateral subtype is again divided into left or right hemiplegia depending on which side is affected, while the bilateral subtype is further divided into diplegia or quadriplegia.[7]

One or more of the following characteristics characterizes the spastic subtype: an abnormal pattern of posture/movement, increased muscle tone, pathological reflexes and/or pyramidal signs.[4,16]

Ataxic CP is characterized by the following: abnormal pattern of posture and/or movement, loss of orderly muscular coordination so that movements are performed with abnormal force, rhythm, and accuracy.[4]

Dyskinetic CP is characterized by an abnormal pattern of posture an/or movement, involuntary, uncontrolled, recurring, occasionally stereotyped movements.[4]

Gross motor function classification system

In recent years, there have been developed methods of classifying CP at an activity level. One of the classification systems that is most frequently used is the Gross motor classification system (GMFCS). In 1997 Palisano and several associates developed GMFCS in order to get a standardized scale for grading the severity of CP. GMFCS is a five-levelled classification system to describe movement-ability limitations in children with CP, across four age bands.[17]

A child's gross motor function is classified by GMFCS in five different levels as follows: [17]

GMFCS I

The child is able to walk without restrictions. Limitations regarding more advanced gross motoric abilities.

GMFCS II

The child is able to walk without aids, but may have imitations when walking outside, e.g. on uneven surfaces, in crowds, inclines and confined spaces, or when carrying objects.

GMFCS III

Are able to walk with aids, e.g. a hand-held mobility device, and may need a wheelchair for longer distances. The limitations in walking may require adaptions in order to enable participation in different physical activities and sports.

GMFCS IV

The child has limitations regarding self-mobility in general. They use methods of mobility that require assistance, that is as physical assistance or in form of a powered mobility in most settings. They may walk for short distances with aids or physical assistance when at home. At school, outdoors and in the community they are transported in a manual wheelchair or a powered mobility.

GMFCS V

The child is transported in a manual wheelchair or in a powered mobility in all settings. The child's ability to maintain antigravity head and trunk postures, as well as control arm and leg movements, is limited.

Manual Ability classification system

The Manual ability classification system (MACS) is a classification system that illustrates how children with CP use their hands in daily day life, especially when handling objects. It is a classification system that enlightens fine motor skills, unlike GMFCS that mainly focus on gross motor skills. The MACS level is under influence by both environmental- and personal factors.

The MACS is as well as GMFCS a five-level system, presented as follows:[18]

MACS I
The child handles objects easily and successfully.
MACS II
The child is able to handle objects, but with some reduced quality and/or speed of achievement.
MACS III
Handles objects with difficulty; needs help to prepare and/or modify the activities.
MACS IV
Handles a limited selection of easily managed objects in adapted situations.
MACS V
The child is not able to handle objects and has a limited ability to preform even simple actions.

1.3 Postural control

Postural control is important for the ability to carry out day-to-day activities and tasks, and can be defined as a person's ability to control the body's position in space for the purposes of stability and orientation.[19,20] Posture describes the relationship between the parts of the body as well as between the body and the external reference frame, the environment and surroundings.[21] Postural control mainly has two main goals; the first one is to maintain balance, to prevent one from tripping or falling over, also called postural stability.[20,21] The other aim is to form an interface between perception and action, postural orientation.[20,21] Therefore, the concept of postural control may be divided into two new subgroups or definitions, postural orientation and postural stability. Postural orientation can be defined as the ability to maintain a correct relationship between the different parts of the body, in addition to the relationship between the body and the surrounding environment, when one performs an action. Postural stability, often referred to as balance, is defined as the ability to control the body's centre of mass (COM), within the support surface, the base of support (BOS).[21,22] Postural control is absolutely necessary in order to be able to maintain stability, which may be defined as the act of maintaining, achieving or restoring the COM relative to the BOS.[23,24] In this thesis, the main focus will be on postural control during quiet stance.

Centre of mass and base of support

Centre of mass (COM) is a defined point in the body described as the centre of the total body mass.[21] In a person, the COM is situated in the trunk.[21,25] Base of support (BOS) is defined as the area of the body or an object that is in contact with the surface.[21] The larger the BOS the easier it is to maintain stability.[26] The BOS will be much larger when seated than e.g. standing on one foot, and the postural control will naturally be easier to maintain in a seated position. When the COM is situated outside of the BOS, e.g. if a person trips and the body suddenly is positioned differently, this will lead to loss of balance and a weakened maintenance of postural control when the COM is situated outside of the BOS.[23,24,26] In order to maintain a vertical alignment and thus postural control, one has to move and reposition the body. This may mean move the body together with the legs during gait, or to move the body back and forth in order to adapt to unavoidable spontaneous changes in different mechanical characteristics of the vertical posture, called postural sway.[21] Because the BOS is larger when a larger part of the body is in contact with the support surface, people with CP whom studies show have greater problems with postural control than people without CP, often choose to maintain seated instead of standing.[21]

1.3.1 CP and postural control

Studies show that people with CP have problems with postural control, and the reasons for this are many and varied.[1,21,27] Postural control requires a complex interaction between neural and musculoskeletal systems.[20] In the musculoskeletal system, postural control depends on components such as joint range of motion, muscle properties and biomechanical relationships among linked body segments. In the neural systems, postural control depends on components such as proprioception, neuromuscular synergies, the visual, vestibular and somatosensory system in general and last but not least a higher level of integrative processes, that is higher neural processes such as cognitive influences on postural control.[20] Many of these components may be compromised in a person with CP.[20,21]

Individuals with CP, especially those with spastic CP, may have hypertonia and spasticity[5]. Spasticity is defined as a "motor disorder characterized by a velocity-dependent increase in tonic stretch reflexes with exaggerated tendon jerks, resulting from hyperexitability of the stretch reflex" [20], and is often caused by lesions in the pyramidal tracts or the descending motor pathways nearby, which is very often seen in persons with CP.[20,28] This spasticity may often present it self in the calf and the musculature in the lower extremities.[28] Prolonged hypertonia and spasticity may lead to contractures, a permanent shortening of the musculature, in the musculature, e.g. in the lower extremities and in the calf-musculature. Many of the individuals with contractures do not have the ability to distribute the weight load of their body. Hence, this weight load will often be situated in the forefoot.[20,28] This will reduce the BOS and worsen their ability to control posture. Hypertonia and spasticity may also lead to dislocation and joint deformities. This will compromise the posture and vertical alignment of the body and thus make it more difficult to maintain postural control.[28]

Alignment of the body may also be affected in individuals with CP. Naturally; this may also cause problems regarding postural control. Alignment of the body refers to the arrangement of body segments to one another as well as to the gravity and base of support.[21] Changes in alignment and/or body position are often characteristic for people with neurological deficits, e.g. CP. Many persons with CP show restricted range of motion in many joints, in addition to contractures of the hip, knee and ankle muscles. This may lead to atypical, often crouched postures whilst sitting and standing.[28] The best alignment in order to obtain and maintain postural control is when the body is placed in a vertical position and every segment of the body is placed in a straight vertical line on top of each other.[21] Because of joint deformities and contractures and an in general crouched position, some individuals with CP will have a compromised alignment and thus postural control.

Postural control is a complex interaction between many different neural systems and the musculoskeletal system. The sensory system plays an important role in postural control as well, and impaired postural control can therefore be determined by observing not only muscle impairments and biomechanical impairments, but also sensory disturbances. About 90% of persons with CP present sensory dysfunction.[29] The main issue in persons with CP is impairments in tactile perception, including sensitivity to pressure, two-point discrimination and proprioception, the ability to be aware of the body segments position and movement in space, without depending on the vision.[21] About 30-50% of persons with CP also have visual impairments, which naturally also will have an impact on postural control.[20]

1.3.2 Postural control during quiet stance

Control of posture during quiet stance is normally divided into two categories: 1) steady state balance control, involving body alignment and body sway, and 2) postural adjustments to externally and internally triggered disturbances.[21] These adjustments include both responses to unforeseen trips or slips, called reactive postural adjustments (RPA's), as well as adjustments made before a voluntary movement: anticipatory postural adjustments (APA's).[30-32] APA's are those adjustments made by the body in order to prepare for the disturbances to body alignment and position expected when initiating a movement or action.[20,31] For instance, when a person is about to lift an arm, the first adjustments in specific direction-specific muscles, both agonists and antagonists are activated before the initiation of the movement.[21,33] The ability to generate APA's is absolutely necessary in order to maintain postural control while moving. When a person trips or slips involuntarily, the APA's are eliminated. That is when RPA's become important.[20] The RPA's are the adjustments made after a movement in order to maintain postural control. Studies show that individuals with CP often lack some of these postural adjustments, both preparatory and reactive.[21,30,32]

When an individual attempts to stand still, several spontaneous movements are activated in order to maintain posture. Two important movements are; change in location of COM (which is often measured and expressed with movement of COP) and change in trunk inclination. These movements define the postural sway.[21] Several researchers claim that individuals with CP have an increased postural sway compared to typically developed (TD) individuals.[21,26,34] The reasons for this assumption are many. Studies have shown that children with CP show increased displacement of COP when the postural control is challenged, compared to typically developing (TD) individuals [34], and hence may have an increased postural sway. In addition to this, it is shown that postural adjustments usually are delayed in an individual with CP compared to TD individuals, and that the postural control of individuals with CP is challenged by smaller perturbations, which will cause greater variability in movement. It also takes them longer to

recover stability because of a co-activation of agonists and antagonists that will be inexpedient for their postural control.[20,21] This co-activation will also cause higher energy consumption in individuals with CP, and they will tire faster that typically developed individuals.[20,34] These observations may indicate that CP individuals have an increased postural sway compared to TD individuals.

1.3.3 Assessment of postural control in individuals with CP

There are many interventions proposed to improve postural control in individuals with CP including trunk targeted training, hippotherapy, horseback riding, constraint-induced therapy, electrical stimulation, virtual reality training, adaptive seating and training on a moving platform[23,35] in addition to e.g treatment with Botulinum neurotoxin (BoNT) for improving gait and function [36],[37] (and many others). In order to evaluate the effect of such interventions, there is a need for appropriate measurement tools to assess postural control in individuals with CP.[35]

However, there is no common agreement on how balance and postural control should be assessed in a regular clinical setting in individuals with CP. There has been very limited research on postural control in general as well as dysfunction in postural control in individuals with CP, regarding both classification, assessment and treatment.[38] In 2013 two systematic reviews were published regarding evaluation of postural control in a clinical [23] and laboratory [26] setting. Laboratory tools used to measure postural control such a force plates, electromyography and kinematic analysis showed quite good results regarding validity and reliability, while the clinical assessment measures had limited evidence.[38]

A much used assessment tool in a laboratory setting is the use of force plates to e.g. measure displacement of centre of pressure (COP) and thus postural control.[26,39] COP refers to the point where the pressure of the body over the soles of the feet would be if it were concentrated in one spot.[40] COP is often used when one wants to quantify postural control and postural sway in people with CP (and in people without CP)[40], as COM may be very difficult to measure and assess in a clinical setting. Most of the laboratory assessment tools employ force platforms to evaluate postural control, e.g. by measuring COP displacement over time.[26,39] The downsides to such measurement tools are e.g. the cost and the limited access to the equipment required, which can only be found in laboratories and thus can not be used in a easy accessible, clinical setting.

According to a systematic review published by Sæther et al. in 2013 it is difficult to find a single, clinical balance tool that can assess postural control since it is such a complex construct.[23] Another study published recently by Dewar et al. in 2016 also found that there are limited

consensus on postural control assessments in a clinical setting that are valid and reliable for children with CP.[38]

The 22 clinical assessment tools evaluated in the study published by Saether et al. in 2013 focused on one or more of the three main categories of postural control: maintaining, achieving and restoring it.[23] There was limited evidence for the measurement properties of most of the assessment tools evaluated. Some of the existing clinical assessment tools for postural control during quiet stance are the Berg Balance Scale, Functional Reach Test and Timed Up and Go[23], but the majority of the assessment tools have limited levels of evidence, especially regarding construct validity, reliability and responsiveness (sensitivity to change).[23] Thus there is still a need for assessment tools with high quality documentation of these measurement properties, easy accessible for use in clinical settings.[23,38] In our study we have evaluated the possible use of a new assessment tool for postural control easy to use in a clinical setting: a computer-based video analysis software that may be able to quantify postural movements in individuals with CP.

When evaluating the quality of a new measurement property or assessment tool, one evaluates its measurement properties. The COnsensus-based Standards for the selection of health Measurement Instruments (COSMIN) have proposed a checklist manual in order to increase the quality of how measurement properties, such as validity, reliability and responsiveness, are studied.[41,42]

In line with this checklist manual, validity is defined as the degree to which an assessment tool measures what it is supposed to measure.[42] Face validity is defined as the degree to which the assessment tool looks as though its measures are an adequate reflection of the construct to be measured. Construct validity is defined as the degree to which the scores obtained from the assessment tool are consistent with the hypothesis, e.g. in relationship to other assessment tools.[41-43] Reliability is defined as the degree to which the assessment tool is able produce consistent results, e.g. on different occasions, when there is no evidence of change in the construct to be measured.[42] Responsiveness is defined as sensitivity to change; i.e. the ability to measure change over time in the construct to be measured.[42] This study has evaluated the validity of the computer-based video analysis software for quantifying postural control in individuals with CP.

1.5 Computer-based video analysis

Technologies that have the ability to capture movements (*motion capture technology)* give the opportunity to quantify human movement based on objective criteria. Several methods have been developed in order to measure and evaluate human movement, but there are several drawbacks to many of these methods. Cost is one issue, another is that these systems and methods often require extensive equipment and need to be performed in very controlled settings. In addition, the unnatural laboratory setting may often make the performers and patients uncomfortable and this may compromise the quality of the results.[44] During recent years a *computer vision* system with the ability to describe and understand human movement by creating *motion images* [44,45] from video recordings made by a normal 2D video camera, have been developed to study music related movement [44-46] and to evaluate and quantify spontaneous movements (general movements) in young infants.[47,48] This computer-based video analysis software quantifies movement patterns from a video recording and makes assessment of movements independent of visual observation. Costs are low, and the method does not require any other equipment than a video camera and the computer software. The computer-based video analysis was developed based on the Musical Gesture Toolbox [49] and creates a motion image by calculating change of pixels between every frame in the video sequence.[50] This computer-based video analysis software exports several variables, describing movement in different planes and axes. The relevant variables for this study will be described under method and materials. However, it is unknown whether the computer-based video analysis is able to quantify postural control and if it is valid for the assessment of postural control in individuals with CP.

1.5 Aim of the study

Hence, the first aim of this study was to explore how computer-based analysis software can be used to assess postural control, and which variables from the computer-based video analysis that best predict postural control.

The second aim was to describe the measurement properties face validity and construct validity of the computer-based video analysis in individuals with CP, 9-29 years of age. In the study of face validity, we hypothesized that the observations of movement from the video recordings would coincide with the calculations from the computer-based video analysis. Regarding construct validity we hypothesized that the correlation between the scores on this new measurement tool and the scores obtained from a commonly used clinical assessment of motor function would be high (>0.70) (the Gross Motor Function Measure item set 66 (GMFM-66_IS)). To strengthen the evidence for construct validity we hypothesized that participants with CP would have scores that differed from participants with TD.

2. Methods and materials

2.1 Study design and participants

In the first part of this study I explored, in collaboration with medical student Mali Kanstad, which of the variables calculated by a computer-based video analysis software that best predicted postural control in subjects with and without CP. In the second part of the study I have explored face- and construct validity of this computer-based variable.

Eligible for participation were individuals with CP and TD individuals, 9-29 years, who were able to understand instructions and to stand still without support for minimum 30 seconds. There were no limitations regarding CP subtype. The individuals with CP attended Beitostølen Healthsports Centre (BHC) for a three week individualized, intensive training program. Originally, they took part in another study on the validity and responsiveness of different clinical assessment of postural control in a sitting position.[51] The participants with CP were recruited during June to November 2013 at the start of the training period at BHC. Fourteen were originally included in the present study. However, one individual was excluded because she was not able to stand without support in 30 seconds on the day she was tested. The 24 individuals without motor impairment (the TD group) were recruited among medical students and children of employees at St. Olavs University Hospital during October 2016.

Table 1

Characteristics of individuals with CP and TD individuals participating in the present study.

All children			Children with CP			
	All	TD	CP	GMFCS I	GMFCS II	GMFCS III
N	37	24	13	9	3	1
Unilateral, n			10	8	1	1
Bilateral, n			3	1	2	0
Male gender, *n* (%)	16 (43)	10 (42)	6 (46)	3 (33)	3 (100)	0
Age (years), mean (SD)	20,0 (7,2)	20,6 (6,8)	18,9 (8,0)	18,0 (7,7)	23,3 (9,8)	14
Height (cm), mean (SD)	167,4 (14,4)	170,3 (13,7)	161,8 (14,6)	159,6 (14,8)	168,8 (17,5)	161

2.2 Variables:

Cerebral palsy was diagnosed in line with the criteria and classification proposed by the SCPE.[4] Gross motor function was classified using the Gross Motor Function Classification System (GMFCS)[17].

2.2.1 Gross Motor Function Measure 66 item set

The Gross Motor Function Measure 66 item set (GMFM-66-IS) is a short version of the original Gross Motor Function Measure (GMFM).[52,53] This is an assessment tool designed to evaluate gross motor function, including postural control, in individuals with CP.[54] This abbreviated version has been developed in order to reduce the burden on the children and the therapists. The original GMFM consists of four different item sets, categorized into five different dimensions, A) lying and rolling, B) sitting, C) crawling and kneeling, D) standing and E) walking, running and jumping. Item set 1 consists of dimension A, B and C (0-45 points), item set 2 of dimension A, B, C, D and E (0-87 points), item set 3 of dimension B, C, D and E (0-117 points), and item set 4 of dimension B, D and E (0-66 points). The participants in this study qualified for item set 4. Calculation of the GMFM-66_IS scores was performed using the Gross Motor Ability Estimator. The GMFM-66_IS has been found to be reliable (inter-tester and test-retest, ICC 0.92-0.99) and valid (construct validity) in children and adolescents with CP.[51,52] In this study dimension B, "sitting", of the GMFM-66 Item set 4 was excluded from the analyses, as it consisted of only one test and was not suitable for correlation analyses.

2.2.2 Computer based video analysis software

All video recordings (further explained in *assessment procedure, chapter 2.3.1)* were assessed using the computer-based video analysis software. Figure 1 presents a screenshot of the computer-based video analysis software used in this study. The video recordings made with a normal 2D video camera (further described in *chapter 2.3.1*), were used as input to the software, and a "motion image" was calculated" using frame differencing in the computer-based video analysis software (Figure 1).

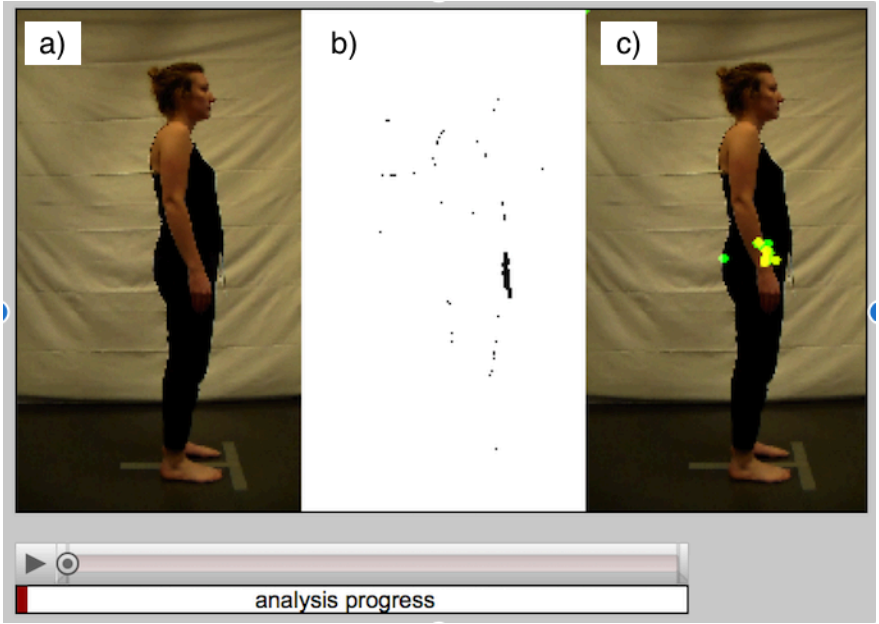


Figure 1. *Screenshot of the computer-based video analyse software while analysing a video recording.*
(a) The input video; (b) the motion image, black areas represent movement, white areas represent no movement; (c) the centroid of motion plotted in green and yellow on top of video.

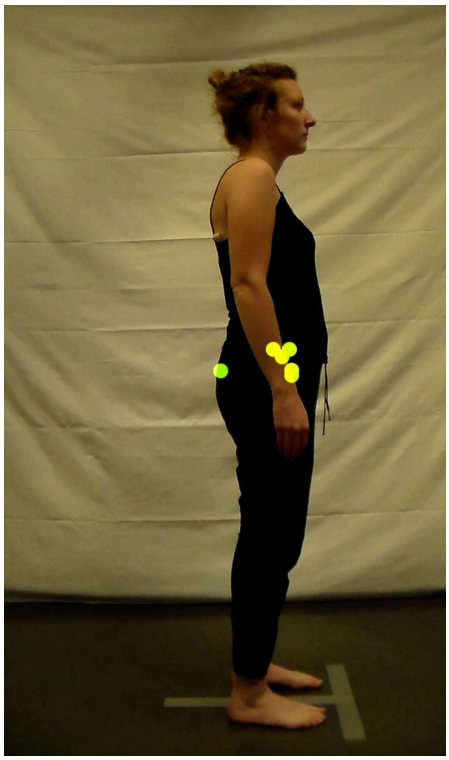
Variables from the computer-based video analysis

The computer-based video analysis software calculates a high number of variables from the motion image, assessing different aspects of movement through the video recording (Appendix, Table 5). The different variables describe e.g. the height of movement, the area of movement, width of movement, the total amount of movement (Quantity of motion) and the spatial centre of movement (Centroid of movement). The variables are calculated as mean and standard deviations for each variable and each individual. In the first part of the study we ran initial correlation analyses in order to get a general idea of which variables would best predict postural control by evaluating the correlation with GMFM-66 Item set. We concluded that the amount of motion, quantity of motion, as well as the spatial centre of motion, the centroid of motion, would be best fit to predict postural control and thus be used in further analyses.

The amount of motion, the quantity of motion, calculated from the motion image, is defined as the total amount of active, or changing pixels from one frame to the next, divided by the total amount of pixels.[50,55] If quantity of motion is 1, this means that all the pixels have changed from one frame to the next. If there is no movement at all, the quantity of motion will be 0. Quantity of motion can be illustrated in images as seen in figure 2. The white areas illustrate that no pixels have changed from one frame to the next, whereas the black pixels illustrate movement. We used illustrations (motion images) of the calculations of quantity of motion made by the computer-based analysis software to evaluate which filtering settings to apply when calculating the final, most accurate motion image (further assessed under *Filtering of the motion image*)

Figure 2. *The figure presents an illustration of the quantity of motion throughout the video recording. The white areas represent no motion, while the black areas represent the pixles that have changed during the entire video. In this example, sharp and black lines illustrate movement in the trunk throughout the video and more greyscale areas in head, arm and leg illustrate that some motion has been present.*

The centroid of motion is defined as the spatial centre of all the active pixels in the motion image and can be calculated for horizontal (x) and vertical (y) directions (movements). The centroid of motion in the horizontal plane may be seen as a correlate to the centre point of all horizontal movements in the video recordings. The positioning of the centroid of motion is illustrated as seen in figure 3. There are two main variables describing the centroid of motion: Cx_{mean} and Cx_{SD}.. Cx_{mean} describes the average displacement of the centroid of motion in the horizontal axis through the entire video sequence. Cx_{SD} describes the variability of displacement of the centroid of motion. Thus, we imagined that these variables might be able to quantify postural movements in the horizontal axis. By the end of the first part of this study, we concluded that these were the two variables best suited for further analyses of face and construct validity.



Fgure 3. *An illustration of how the centroid of motion changes throughout the video recording. The green and yellow dots illustrates the placement of the centroid of motion for each frame during a short video clip*

Filtering of the motion image

In previous studies [48,50,56] the filtering of the motion image; that is how sensitive the calculation will be for movement, have been set to 0.05 (young infants often show a lot of spontaneous movements in a video sequence). In this study our participants were told to stand still and we needed to experiment with some filter settings to identify the optimal setting. An optimal setting would filter noise in the video; like pixels changing due to movements in the background, lighting conditions etc., while simultaneously keeping information about pixels changing due to real movements in the participant. Hence, we experimented with four different filtering settings: 0.01, 0.02, 0.03 and 0.05. After observation of the different motion images (fig. 2) we identified a filter setting of 0.02 as the optimal setting (Fig. 4)

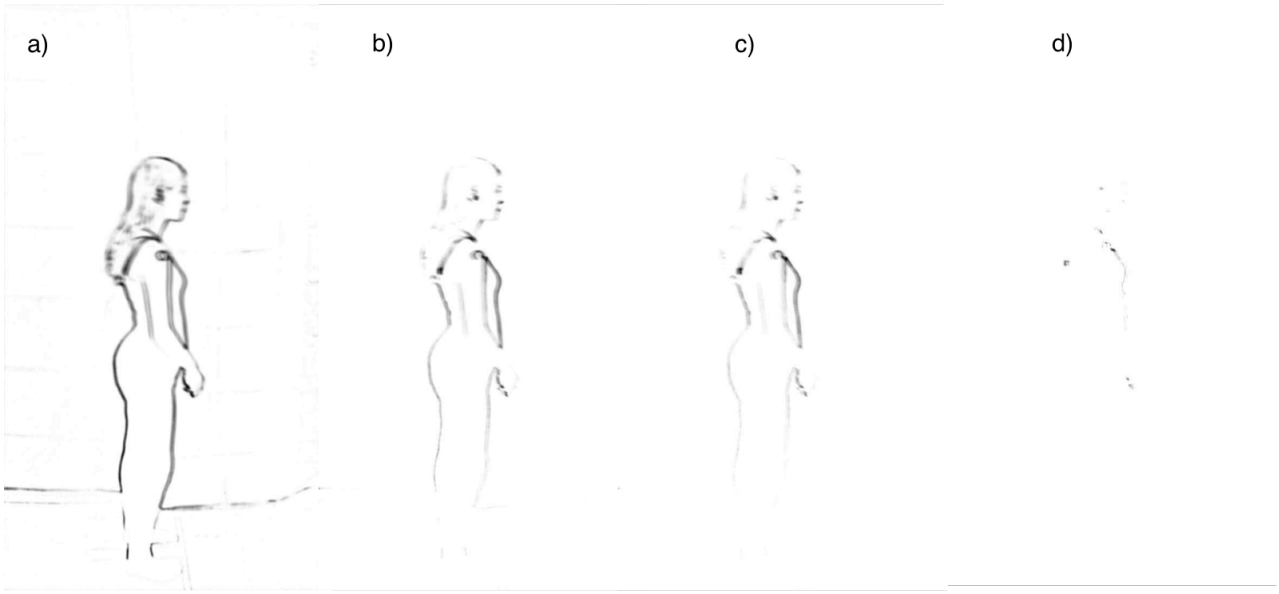


Figure 4. Illustration of the motion average images from four different filtering settings: a) 0.01, b) 0.02, c) 0.03 and d) 0.05. After evaluation of the four different motion average images, we concluded that the filter setting 0.02 would be the best filtering setting to use in order to exclude irrelevant movement and include as much relevant movement as possible. In illustration a) too many irrelevant elements contribute to the motion average image, such as the background and floor. In illustration b) only movements of the participant contribute to the motion average image, clearer than in illustration c).

2.3 Assessment procedure

Repeated video recordings of quiet stance of the participants with CP were performed at the arrival of their stay at BHC in 2013. After the video recordings, the participant performed the GMFM 66 item set. Repeated video recordings of quiet stance of the participants without CP were performed during October 2016 in Trondheim.

2.3.1 Video recordings

The camera set-up was standardized with respect to background, lighting and placement of the participant. All participants were told to stand still, without shoes and with 25 cm between their feet (Fig.5). The participants with CP were dressed in black or with only shorts and a light top/shirtless. The participants without CP were all dressed inn dark clothing, a singlet and pants. A Samsung HMX-F90 camera placed as shown in figure 5 was used to obtain the video-recordings. The purpose for this positioning of the participants presented in fig. 5 was to be able to detect anteroposterior postural movements.

The participants were asked to stand still during the recordings. They were video recorded for 30 seconds in the first and second recording and 2 minutes in the third recording, resulting in a total of three different video recordings. In between the three recordings, they had a break for a few minutes where they were told to do something different than standing still, for instance walk around, sit down etc.

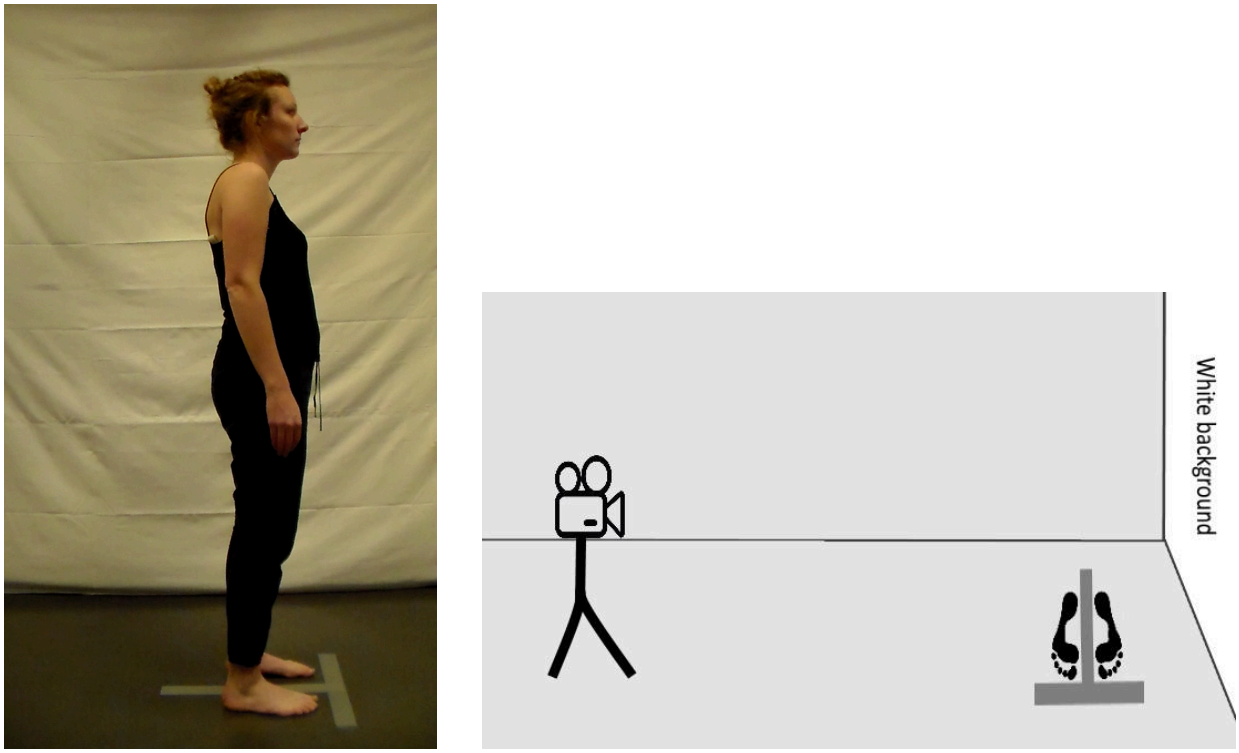


Figure 5. *Illustration of video assessment and how the participants were placed in relation to the camera*

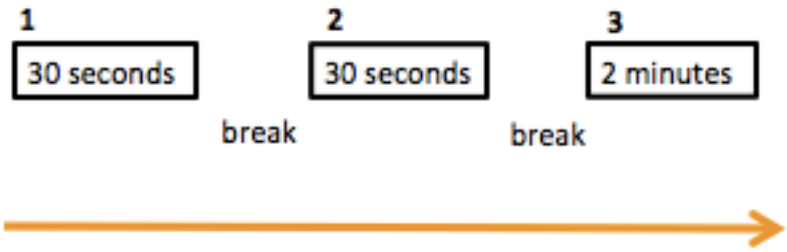


Figure 6. A timeline illustrating the video recording process.

2.3.2 Computer based video-analyses

The video material from video recording 1 and 2 were trimmed excluding 4 seconds in the beginning to exclude initial movements in the video before the participant focused totally on standing still. These were irrelevant movements, such as turning to talk to examiner, scratching etc. This was only an issue in some of the first and second video recordings, but we chose to edit all of them in order to have a consistent length. Consequently, all first and second videos used for further analysis were 25 seconds long. The third recordings of 2 minutes did not have the same problem and were not trimmed, as all of the participants were already satisfyingly positioned and standing as still as they could without irrelevant movement from the initiation of

recording and through the entire sequence. The resolution of 1080x608 pixels and 25 frames per second was identical for all recordings. The final trimmed video material was used for the computer-based video analysis and calculation of the motion variables.

2.4 Statistics

All variables were examined by the Kolmogorov-Smirnov test, and indicated that the variable Cx_{mean} for all recordings was normally distributed. The variable Cx_{SD} for all recordings was not normally distributed. However, in line with Geoff Norman and other statisticians we also used parametric tests to compare the mean values of the latter variable between groups.[57] Moreover, mean and standard deviation (SD) were used to report location and distribution of the variables Cx_{mean} and Cx_{SD}.[58]

Face validity was examined by observing whether the variability of the centroid of motion calculated by the computer-based analysis software coincided with observable movements in the participants during the video recordings.

Differences in mean values of C_{mean} and C_{SD} between individuals with CP and TD individuals, as well as TD individuals and individuals with GMFCS level I and II+III, were assessed by Student's t-test and analyses of variance. Differences between groups were also examined and adjusted for a possible confounder, clothing, using a general linear model.

Construct validity was examined by assessment of the relationship between the scores on the computer-based video analysis and the GMFM-66 Item set scores using the Pearson correlation coefficient and Spearman rank correlation. As proposed by Portney and Watkins[59] correlation coefficients between 0-0.25 may be considered to indicate little or no relationship, correlations from 0-25-0.50 indicate low, between 0.50-0.75 indicate moderate to good, and above 0.75 may be considered to indicate a good to excellent relationship.

Data derived from the video recordings were analysed and transformed to excel using Matlab version 2015a. Further analyses of the processed data from the video recordings and GMFM-66 Item set were analysed using SPSS version 24.0. (SPSS Inc, Chicago IL USA). In order to correct for between-subject differences in body size, all variables were divided with the height of the subjects measured in pixels in the video recording. To make interpretation easier, we scaled all the variables by multiplying them with 100.000.

Two-sided p-values <0.05 were considered statistically significant, and 95% confidence intervals (CI) were reported when relevant.

2.5 Ethics

The study was conducted in conformity of the Declaration of Helsinki. The Regional Committee for Medical Research Ethics in Northern Norway considered that ethical approval was not required according to Norwegian regulations (reference: 2013/355). Nonetheless, we obtained written informed consent from the participants and from parents.

3. Results

In the explorative part of this study the initial correlation analyses showed that the mean and standard deviation from the quantity of motion and the centroid of motion were the variables that correlated best with GMFM-66 Item set and the two dimensions: D: "standing" and E: "walking, running, jumping". The other variables showed no significant correlations (Appendix, Table 5). After further analyses, the variable with the highest correlation coefficients was the centroid of motion mean (Cx_{mean}). However, closer observation of the data and the videos indicated some limitations regarding the quantity of motion variables (Q_{mean}). These limitations included lower scores for Q_{mean} in individuals with CP than in TD individuals, whereas in the observations of the videos, CP individuals had generally more movements. Moreover, the calculations of Q_{mean} were significantly affected by differences in clothing. These limitations were less accentuated for the centroid of motion, and we therefore decided to further explore the mean and standard deviation (as an indicator of the variability of the centroid of motion throughout the video recording) of the centroid of motion in the horizontal plane. In the second part of this study I therefore explored face- and construct validity of these two variables, abbreviated as Cx_{mean} and Cx_{SD}. In another student thesis, my colleague, Mali Kanstad has explored test-retest reliability of the same variables.

3.1 Validity

3.1.1 Face validity

Figure 7 shows the calculations of the centroid of motion from the computer-based video analysis throughout the 30 seconds of the first video recording for two participants with CP, illustrated in graphs (plots). Observations of movement from the same video recordings identified periods were the participant was standing still, had a movements forward and movements backwards (possibly postural movements and adjustments). Large deviations from the mean value on the graph correlated well with large body movements observed in the videos, while small deviations correlated with smaller body movements. When observing the video recordings, we also observed that participants with poorer alignment, e.g. standing with a crouched posture, presented greater mean values for the centroid of motion than participants with a more upright posture and alignment. These results suggest that the variability of the centroid of motion, reflected in Cx_{SD} may indicate postural sway, whereas the mean value of the centroid of motion (Cx_{mean}) may reflect body posture in space, the alignment of the participant, when the person attempts to stand still.

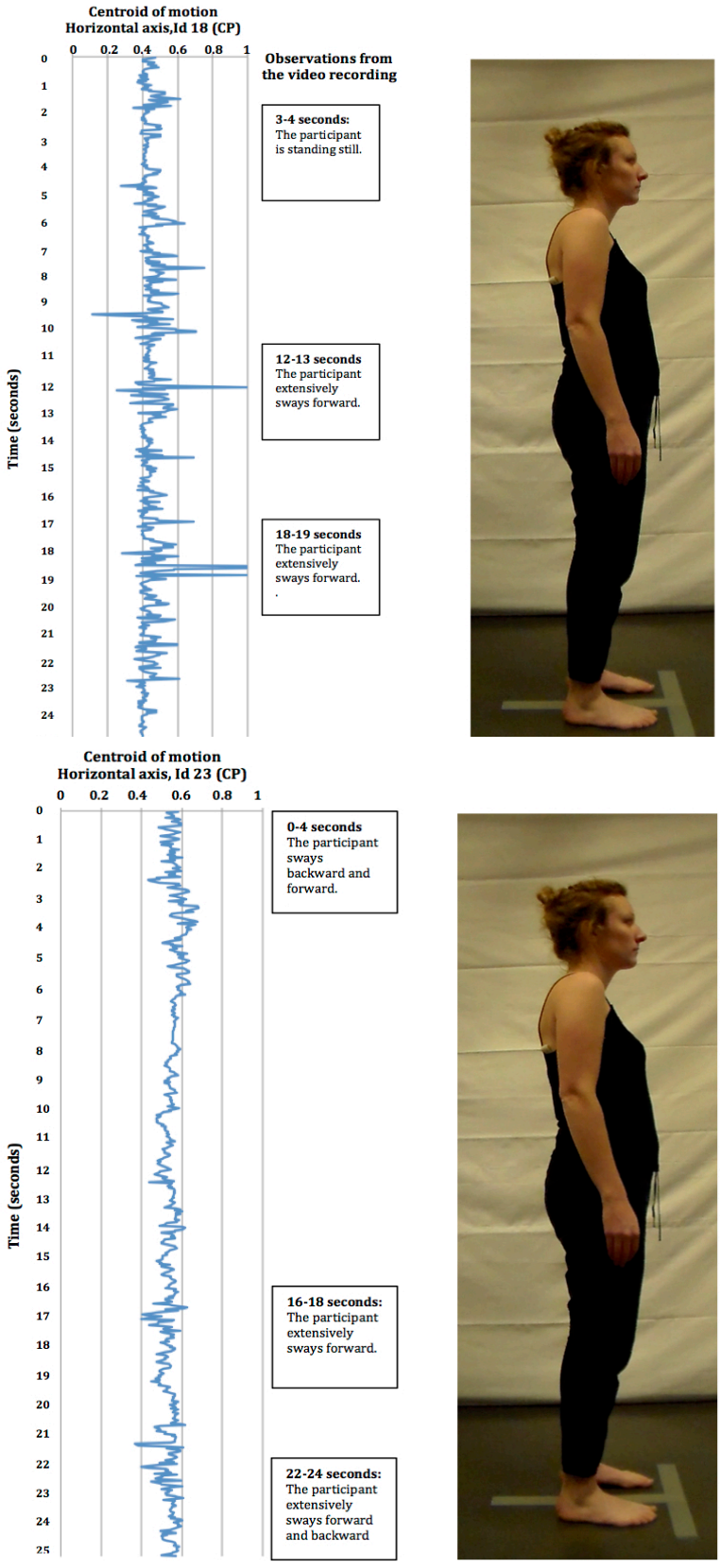


Figure 7
The plots illustrate the calculations from the computer-based video analysis of the centroid of motion throughout the first video recording from two of the particpiants with CP. A spike towards the right represents the persons movement forward, a spike towards the left represents the persons movement backwards. Movement observations made at specific moments in the recordings are described in boxes. The picture to the left is an illustration of the video recording observed.

3.2.1 Construct validity

Twelve individuals with CP were included in the correlation analyses of construct validity. One individual was excluded because another item set of GMFM had been used. The TD individuals were not included in the correlation analyses as the GMFM is developed for use in individuals with CP and is not validated for TD individuals. Table 2 shows that there was a high correlation between Cx_{mean} and GMFM-66 Item set dimension D, "standing", for all three recordings. The correlations between Cx_{mean} and GMFM-66 Item set total score and GMFM-66 Item set dimension E, "walking, running & jumping", were low and not statistically significant (Table 2). The correlations between Cx_{SD} and GMFM-66 Item set were low for all video recordings and all dimensions of the GMFM-66 Item set.

Table 2
Pearson correlation coefficients and Spearman rank correlation coefficients between the motion image variable-scores and total and subscale scores of the Gross Motor Function Measure item set 66 (GMFM-66_IS) in individuals with CP aged 9-29 years.

Motion image variable		GMFM					
		GMFM total		Dimension D		Dimension E	
Rec.no.		Pearson correlation	Spearman rho	Pearson correlation	Spearman rho	Pearson correlation	Spearman rho
1	Cx_{mean}	-0.35	-0.36	0.76**	0.73**	0.55	0.56
	Cx_{SD}	0.09	0.24	0.33	0.26	0.26	0.25
2	Cx_{mean}	-0.44	-0.35	0.68*	0.69**	0.52	0.54
	Cx_{SD}	0.36	0.40	0.40	0.30	0.34	0.38
3	Cx_{mean}	-0.40	-0.37	0.70*	0.69*	0.46	0.53
	Cx_{SD}	0.31	0.47	0.34	0.06	0.29	0.23

GMFM - Gross Motor Function Measure; Dimension D - "standing"; Dimension E - "walking, running & jumping"; Cx_{mean} – Centroid of motion in the horizontal axis mean, Cx_{SD} - centroid of motion in the horizontal axis standard deviation.

** $p<0.01$

* $p< 0.05$

Group differences

The individuals with CP had higher values for Cx_{mean} and Cx_{SD} than TD individuals (Table 3). Figure 8 shows that Cx_{mean} overlapped significantly between the CP and the TD group, whereas there was less overlap between the groups regarding Cx_{SD}.

When examining the difference between groups and GMFCS levels we chose to merge GMFCS level II and III as there was only one participant with GMFCS level III. The values of Cx_{mean} increased with increasing GMFCS level (Table 4). Regarding Cx_{SD}, the individuals with GMFCS level I had higher values for Cx_{SD} than both individuals with GMFCS level II+III and TD individuals, and the individuals with GMFCS level II+III only had higher values for Cx_{mean} than the TD individuals (Table 4).

Table 3
Mean and standard deviation (SD) of individuals with CP and TD individuals for the motion image variables for video recording 1, 2 & 3.

Motion image variable		CP		TD		95% CI	*p*
Recording no.		Mean	SD	Mean	SD		
1	Cx_{mean}	62.0	9.6	55.9	7.0	-11.8 to -0.6	0.032
	Cx_{SD}	5.6	2.8	1.8	0.7	- 5.0 to -2.6	0.001
2	Cx_{mean}	63.3	9.7	55.8	5.0	-13.8 to -1.3	0.021
	Cx_{SD}	5.3	2.0	1.9	0.8	-4.6 to -2.2	0.001
3	Cx_{mean}	61.6	8.6	54.3	6.6	-12.5 to -2.2	0.007
	Cx_{SD}	5.2	1.7	2.0	1.1	-4.2 to -2.3	0.001

Cx_{mean} - Centroid of motion in the horizontal axis mean; Cx_{SD} - centroid of motion in the horizontal axis standard deviation.

Table 4
Mean and standard deviation (SD) for inviduals with GMFCS level I and II+III and TD individuals for the motion image variables from video recording 1, 2 & 3.

Motion image variable		TD		GMFCS1		GMFCS 2+3		*P**
Rec.no.		Mean	SD	Mean	SD	Mean	SD	
1	Cx_{mean}	55.9	7.0	58.8	9.4	69.3	5.3	0.004
	Cx_{SD}	1.8	0.7	6.1	3.2	4.3	0,7	0,001
2	Cx_{mean}	55.8	5.9	59.6	8.7	71.6	6.8	0.001
	Cx_{SD}	1.9	0.8	5.5	2.2	4.7	1.2	0.001
3	Cx_{mean}	54.3	6.6	58.9	8.7	67.6	5.4	0.001
	Cx_{SD}	2.0	1.1	5.7	1.8	4.2	0.8	0.001

Cx_{mean} - Centroid of motion in the horizontal axis mean; Cx_{SD} - centroid of motion in the horizontal axis standard deviation

* ANOVA *p* for linearity.

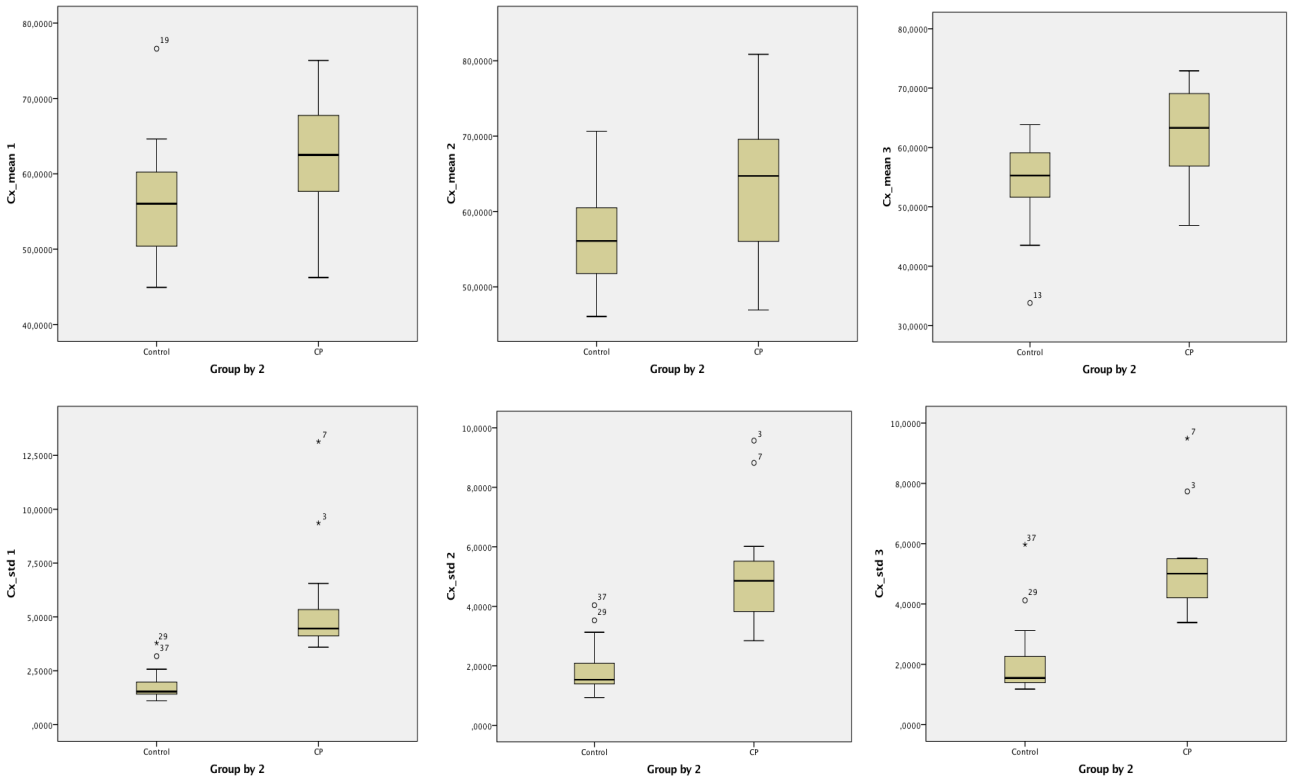


Figure 8
Illustration of the difference between groups (CP and TD) for Cx_{mean} and Cx_{SD} in box plots from the 1st, 2nd and 3rd video recording.
Cx_{mean} - Centroid of motion in the horizontal axis mean; Cx_std = Cx_{SD} - centroid of motion in the horizontal axis standard deviation; GMFCS – Gross Motor Function Classification System level 1, 2 and 3;.Group by 2 – participants are separated in two groups,: individuals with CP and TD individuals.

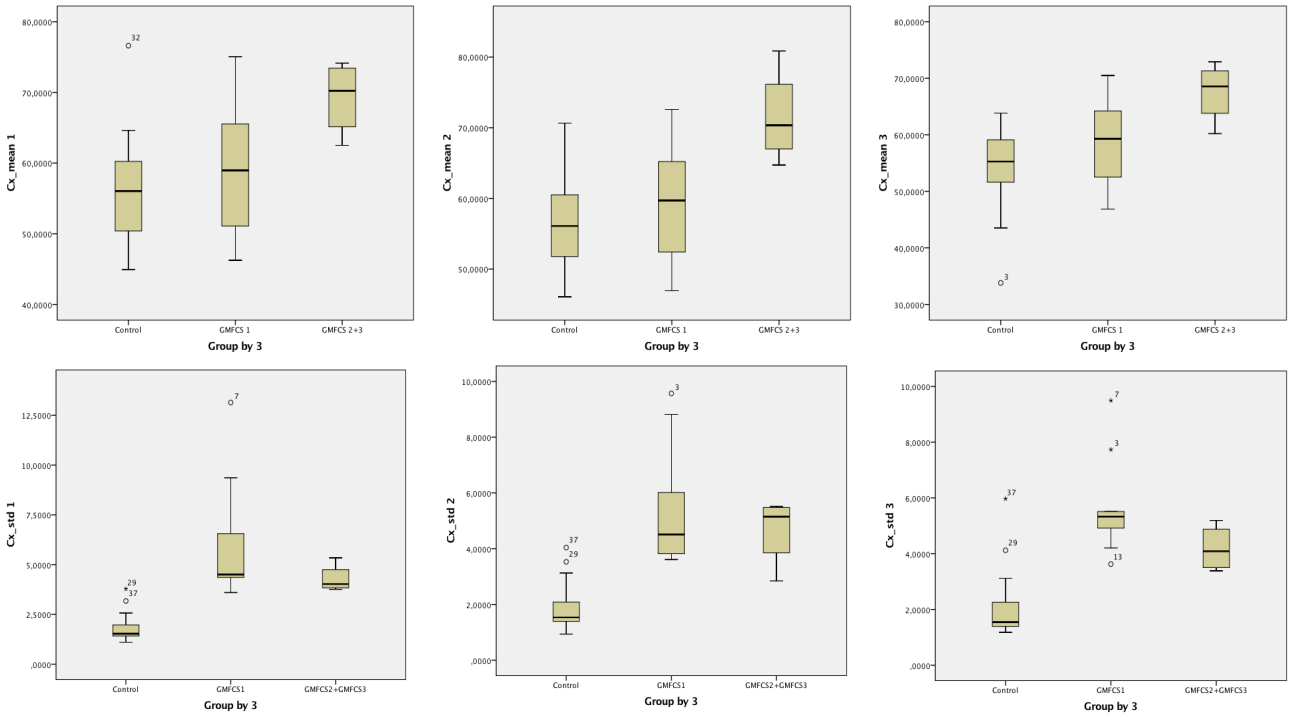


Figure 9
Illustration of the difference between groups (GMFCS level I, II+III and TD individuals) for Cx_{mean} and Cx_{SD} in box plots from the 1st, 2nd and 3rd video recording.
Cx_{mean} - Centroid of motion in the horizontal axis mean for recording 1, 2 and 3; Cx_std = Cx_{SD} - centroid of motion in the horizontal axis standard deviation; GMFCS – Gross Motor Function Classification System level 1 and 2+3; Group by 3 – participants are separated in three groups, individuals with GMFCS level I, levels II+III and TD individuals.

4. Discussion

4.1 Main findings

In this study I found that the mean value of the centroid of motion in the horizontal axis (Cx_{mean}) best predicted postural control as assessed with the GMFM-66 Item set dimension D, "standing". Consistent with the hypothesis, my results from the correlation analyses indicate that there may be a correlation between function during quiet stance, illustrated by the sub score of GMFM dimension D, and the calculations of the variable Cx_{mean} obtained from the computer-based video analysis software in individuals with CP. The mean values calculated for Cx_{mean} were generally higher in the CP group than in the TD group, and the mean value of Cx_{mean} increased with increasing GMFCS level. This may strengthen the construct validity. I also found some evidence for face validity for this variable, as participants who were leaning more forward during standing, had higher mean values.

The observation of movement in the video recordings corresponded well with the calculations and variability of the centroid of motion (expressed as Cx_{SD}), and gave an impression of face validity. Despite this face validity of the variability of the centroid of motion (Cx_{SD}) as a potential indicator of postural sway, the analyses of construct validity were less consistent for this variable, both in the correlation analyses and when comparing the groups based on GMFCS level. Nonetheless, between group differences for the TD and CP groups for Cx_{SD} showed that the CP group had higher mean values than the TD group, which is consistent with our hypothesis.

Another potential indicator of postural sway, the mean value of quantity of motion (Q_{mean}), had important limitations regarding clothing and the interpretation of the data analysis.

4.2 Internal validity

It may be considered a strength of the present study that we have adhered to the COSMIN criteria for measurement properties.

4.2.1 Chance

The correlation coefficients between Cx_{mean} and GMFM-66 Item set dimension D, "standing", are not likely to be caused by chance, nor is the difference between groups for both Cx_{mean} and Cx_{SD}, as indicated by the low p-values. We also observed that the values for Cx_{SD} were higher in the GMFCS level I group than in the group with GMFCS level II+III. This does not coincide with the results we expected, or with the results obtained for the variable Cx_{mean}. However, the number of participants with CP is low, and lack of statistical significance must be interpreted with caution, in particular when we split the CP population into GMFCS levels I and II-III.

According to the COSMIN criteria the sample size of the study is adequate with a minimum of 30 subjects[60], which is considered as a fair sample size. I this study we have 37 subjects. Still, we would have preferred a larger sample size of e.g. 50, which is considered good, or 100, which is considered excellent[60], as well as more diversity regarding GMFCS level, as there was few participants with GMFCS level II-III.

4.2.2 Bias

Selection bias

The participants with CP were recruited at BHC, and it may be discussed if this selected sample is representative of the general population with CP. Individuals with CP who want to participate in an intensive training program could have received more training and rehabilitation and hence have better postural control than the average person with CP and same GMFCS level. On the other hand, to bias the results of the correlations between Cx_{mean} and GMFM-66 Item set dimension D, one has to assume that this relationship is completely different in the general CP population (within the same GMFCS levels). We do in fact observe a systematic difference between groups in Cx_{mean} and Cx_{SD} for all video recordings, and thus there is no reason for assuming that the results will change significantly when the study is performed in a greater study population. Still, there is a possibility that the difference between GMFCS levels will change to more expectant values for Cx_{SD} with a greater study population. Nonetheless, we consider it unlikely that our results are explained by selection bias.

Methodological bias

It may be a possible bias that the participant populations in BHC and Trondheim have been given different instructions during the video recordings. It is important that every participant strictly adhere to the existing guidelines, since the computer-based video analysis program is sensitive to all movement, which means that insignificant movements such as talking, scratching etc may give conflicting results. In some of the video recordings several of the participants at BHC were not ready at the initiation of the recordings, as they were scratching, talking to the examiners etc. To avoid this bias, we had to trim all the recordings (of 30 seconds) by removing 4 seconds from the start of the recordings for each participant.

Another possible methodological problem is the placement of participants in relation to the camera. This is particularly important regarding the Cx_{mean}, as this variable is sensitive to differences in placement of the participant in the video frame. In order to get comparable results, it is important that the participant is standing more or less in the centre of the video frame. An individual standing to the right of the mid-point in the video frame, will give different values for Cx_{mean} than for an individual placed to the left on the same axis. However, we have critically reviewed the different video recordings in our study, and found that overall, the different participants were standing in the middle of the x-axis in the video frame. The calculations of Cx_{SD} do not present the same problem, as Cx_{SD} expresses the variability of displacement of the centroid of motion and thus does not depend on the placement of the participant. This may indicate that the Cx_{SD} is more robust and easier to use, and probably say more about postural sway, whereas Cx_{mean} is an expression the individuals general movements (possibly postural movements, but also other, coincidental movements), as well as the alignment and posture of the participant. Although the value of Cx_{mean} depends on where in the frame the participant is placed, we consider it unlikely that this factor has biased our results.

4.2.3 Confounding

Study site

Potential confounders in this study are differences in age and sex between the participants with and without CP as well as different study sites and differences in how the videos were recorded. There were however no significant differences in the age and sex between the two groups, and we therefore consider confounding by these variables to be unlikely. Possible inconsistencies of the recordings may be related to the camera set-up, positioning of the participant, background and lighting. However, we attempted to copy the implementation done at BHC regarding both camera set-up, including use of the same video camera at the

two sites, and the positioning of the participants, which resulted in that the video recordings seemed more or less technically identical. Thus, we consider we have reduced potential confounding by these factors to a minimum.

The developer of the computer-based video analysis software, A. Jensenius, has in previous research evaluated the importance of background and lighting for the calculation of motion image variables.[45,55] The background in this study was white both during recordings at BHC and in Trondheim. The lighting was slightly different, but previous research has documented that the computer-based video analysis software is quite robust regarding differences in background and lightning[45], and thus, the potential differences in background and lighting are unlikely to have confounded our results.

Another potential confounder was differences in clothing between the participants. While the participants in BHC wore different types of clothing, some wearing black, others wearing shorts and more light clothing or shorts only, all the TD individuals wore black clothing. According to Jensenius[45], clothing is of greater significance for the motion image than background and lighting, and can thus influence the results. What may affect the calculations is a similarity between background and foreground (the participants), such as light coloured clothing on a light background.[45] This may influence the contrast in the video frame and thus the pixels accounted for. For our study this would mean that the participants with only shorts and lighter clothing would have lower values that the participants with black clothing. Nonetheless, if it is still possible to clearly separate the foreground from the background, as in our case, this should not be of great significance for the results. We also found in multivariate analysis that the results for Cx_{mean} and Cx_{sD} were essentially unchanged when we adjusted for clothing (Appendix, table 7 & 8). In correlation analyses we observed that the partial correlation coefficients between Cx_{mean} and Cx_{SD} were even higher than in regular bivariate correlation without adjustment (Appendix, Table 6), but that the adjustment did not have great significance for the correlation results. Thus, we conclude that differences in clothing do not explain our main results. In contrast, our initial analyses (part 1 of this study), suggested that the variable quantity of motion was less robust and more sensitive clothing than the centroid of motion.

4.3 Consistency with literature

This is as far as we know the first study exploring the use of video-based data analyses of postural control, and consequently there is little in the existing literature that can support our specific findings.

Nonetheless, our findings of higher values for Cx_{mean} and Cx_{SD} in the CP group compared with the TD group are consistent with literature indicating that individuals with CP have more problems with postural control, including both alignment and more movements to maintain postural control, than TD individuals.[20,21,34] For the variable Cx_{mean} we also found that the mean values increased with increasing GMFCS level, which is consistent with the literature suggesting poorer postural control with poorer gross motor function[35]. The variable Cx_{SD} did not have the same consistency in mean values, as individuals with GMFCS level I had higher values than individuals with GMFCS levels II+III and the TD participants. Although some studies have indicated that individuals with CP in fact move less during quiet stance than TD individuals. This could be consistent with the results from Cx_{SD}.

In previous studies of the computer-based analysis software used to quantify spontaneous movements in young infants as a possible prediction of cerebral palsy, the variable that has shown to be best qualified and the most robust, is the centroid of motion.[47,50] As stated by Adde et al. in April 2009[50], the centroid of motion may be seen as a correlate to the centre point of total movement of the individual in the horizontal plane and thus be able to quantify postural movements. This coincides with what we found in the initial part of this study (the explorative face): that the centroid of motion was the variable that correlated best with GMFM, and also that the variability of the centroid of motion (Cx_{SD}) and the Cx_{mean} had good face validity.

4.4 Interpretation

In the explorative part of this study, we found that the centroid of motion in the horizontal plane was the variable that correlated best with GMFM-66 Item set dimension D. We excluded the quantity of motion from further analyses, as it seemed too fragile regarding confounders such as clothing. However, as postural control is a complex interaction between many different systems in our body, it is possible that the variable quantity of motion may better quantify other aspects of postural control, as this variable expresses all movement, in all directions, not only movement in the horizontal plane. Nonetheless, the centroid of motion was the most robust variable, depending less on the clothing of the participants. The Cx_{mean} had the highest correlation with GMFM-66 Item set dimension D and showed the

expected increase in mean values from TD participants to participants with CP and GMFCS levels I and II-II, while both Cx_{mean} and Cx_{SD} expressed good face validity.

The moderate to good correlations between Cx_{mean} and GMFM-66 item set dimension D indicates coherence between calculations from the computer-based video analysis program and postural control, and indicate that the values from the computer-based video analysis increase with increasing motor impairments. However, as the Cx_{mean} is an expression of the mean displacement of the centroid of motion and thus depends on where the participant is placed on the x-axis of the video frame, this means that the participants' alignment is of significance for the results. The calculation of Cx_{mean} seemed to be consequently higher for the participants that were standing in a crouched position compared to the individuals with a more upright alignment after studying the video recordings. We do know that the alignment and posture is of great importance for a persons' postural control and thus, the fact that a crouched position will be of significance for the variable calculations, is likely to be of great relevance when quantifying the participant's postural control.

As the Cx_{mean} is a mean value, it does not only quantify movements from side to side, but also other movements, such as movements from the mouth (talking) or movement of e.g. hair (ponytale etc.) in addition to possible postural movements. Thus, Cx_{mean} does not indicate postural sway, but may be just as important regarding quantification of postural control as it seems to express the participants posture and alignment while intending to stand still. This difference in alignment and posture could theoretically be explained by differences in e.g. spasticity and contractures in the calf musculature, whereby children with increasing spasticity have to lean forward to maintain postural control, and thus obtain higher mean values for the centroid of motion. Thus, Cx_{mean} probably indicates one important aspect of postural control: i.e. the alignment of the body in space.

Cx_{SD} expresses the variability of the centroid of motion, and does not depend on the placement of the participant in the video frame. Thus, it is possible that Cx_{SD} may be a better indicator to reflect postural sway. The reason why this variable correlated less well with the GMFM-66 Item set may be due to the fact that this clinical assessment tool and its dimension D, "standing", is unlikely to be a direct expression of postural sway. The items of the GMFM-66 Item set dimension D, are e.g. to lower to a sitting position without using arms, standing on one foot, attain standing through half knee on each knee and attain a squat position. These items are clearly dependent of postural control, but if the aim is to study sway, one should choose another reference method than the GMFM-66 Item set. This could explain the low correlations between Cx_{SD} and GMFM-66 Item set. Another

assessment tool, better reflecting postural sway might therefore have resulted in better correlations. Nonetheless, it is problematic that Cx_{SD} did not show a consistent increase or decrease with increasing GMFCS levels.

4.5 Clinical implications

A strength of the computer-based video analysis software is that is that a single task can be used both for the clinical evaluation and for the computer based assessment. The method is objective, in contrast to many clinical tools that are subjective assessments. Finally, the necessary equipment is easily accessible, of relative low-cost and easy to use. This makes the computer-based video analysis software accessible for assessment in many different clinical settings and locations. However, the method is very sensitive to variations in placement of the participants, instructions given to the participant, clothing (especially Q_{mean}) and camera set-up. Thus, exact instructions are needed if the method is introduced in clinical practice

Regarding the placement of participants in the video frame, it is important that the placement of patients is consistent. I could also be a possibility to crop all videos after the recordings to make sure that each participant is placed at the same place in the frame. I would suggest that a user's manual with strict guidelines regarding camera set-up, instructions given to the participants, placement of the participants and implications regarding clothing is developed for future research of this method. Adherence to such guidelines could eliminate many of the possible biases and confounders we have found in this study.

4.6 Implications for future research

I believe that the computer-based video analysis software indeed may be used to quantify postural control in individuals with postural control, but that this method need further investigation. First of all it should be investigated with a greater study population and more diversity regarding GMFCS level. In future research I would also recommend to be more consistent with clothing and see if this could make quantity of motion (Q_{mean}) easier to use, as this variable is able to capture all movements in the motion image, not only movements in the horizontal axis.

For future research, it would also be of interest to study the construct validity of other variables. In previous studies [48,50,61,62], a new variable have been created based on both x- and y-values for the variability of the centroid of motion, called C_{SD}.[50] This variable is based on the calculations of variability in the x- and y-direction, and is thus able to quantify *all* postural movements in both the horizontal- *and* vertical plane. This could possibly give a

more correct quantification of postural control. Another variable that has shown to have importance regarding early prediction of CP by observing spontaneous movements in young infants, is a variable called CPP that has the equation CPP=(a x Q_{mean}) +(b x Q_{sd})+(c x C_{SD}). This is further explained in another article.[48] For future research, I would suggest to investigate the correlation between CPP and GMFM-66 Item set, as this variable has shown to have great importance in other studies.[48]

In order to study postural sway, another important aspect of postural control, it would be interesting to use another assessment tool with better evidence for postural control for the correlation analyses than GMFM-66 item set, such as force plates.[38]

5. Conclusion

I have found that Cx_{mean} calculated by a computer-based video analysis software may be used to asses postural control during quiet stance in individuals with CP. Two other variables, Cx_{SD} and Q_{mean} may have the potential to describe postural sway, but future studies are needed to document this.

6. References

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Appendix

Table 5
Pearson correlation coefficients and Spearman Rank correlation coefficients between all motion video variables and total and subscale scores of the Gross Motor Function Measure item set 66 (GMFM-66_IS) in individuals with CP aged 9-29 years for recording 1.

Motion image variable	GMFM					
	GMFM total		Dimension D		Dimension E	
	Pearson correlation	Spearman rho	Pearson correlation	Spearman rho	Pearson correlation	Spearman rho
aom_mean	-0.34	-0.23	-0.13	-0.12	-0.34	-0.38
aom_sd	0.06	0.03	0.16	0.21	0.04	0.08
hom_mean	-0.25	-0.32	-0.01	-0.13	-0.30	-0.36
hom_sd	0.02	-0.10	0.33	0.34	0.38	0.40
wom_mean	-0.30	-0.32	0,03	0.13	-0.24	-0.18
wom_sd	0.06	0.03	0.16	0.21	0.04	0.08
com_t_mean	-0,34	-0.23	-0.13	-0.12	-0.34	-0.38
com_t_sd	0,06	0.03	0.16	0.21	0.04	0.08
com_r_mean	-0.34	-0.23	-0.13	-0.12	-0.34	-0.38
com_r_sd	0.06	0.03	0.16	0.21	0.04	0.08
com_t_mean2	-0.34	-0.23	-0.13	-0.12	-0.34	-0.38
com_t_sd2	0.06	0.03	0.16	0.21	0.04	0.08
com_r_mean2	-0.34	-0.23	-0.13	-0.12	-0.34	-0.38
com_r_sd2	0.06	0.03	0.16	0.21	0.04	0.08
Q_{mean}	-0.64*	-0.33	0.30	0.22	0.06	0.05
Q_{SD}	-0.50	-0.41	0.03	0.13	-0.21	-0.12
Cx_{mean}	-0.25	-0.36	0.76**	0.73**	0.55	0.56
Cx_{SD}	0.14	0.24	0.36	0.26	0.38	0.25
Cy_mean	0.11	0.20	0.62*	0.67*	0.24	0.32
Cy_sd	0.03	0.18	0.17	0.03	0.17	-0.05

** p <0.01

*p <0.05

Table 6

Pearson correlation coefficients and Partial correlation coefficients between the motion image variable-scores (Cx_{mean}) and total and subscale scores of the Gross Motor Function Measure item set 66 (GMFM-66_IS) in individuals with CP aged 9-29 years

Motion image variable		GMFM					
		GMFM total		Dimension D		Dimension E	
Rec.no.		Pearson correlation	Partial correlation	Pearson correlation	Partial correlation	Pearson correlation	Partial correlation
1	Cx_{mean}	-0.35	-0.26	0.76**	0.81**	0.57	0.62*
	Cx_{SD}	0.09	0.18	0.33	0.32	0.26	0.32
2	Cx_{mean}	-0.44	-0.40	0.68*	0.79**	0.52	0.67*
	Cx_{SD}	0.36	0.50	0.40	0.36	0.34	0.37
3	Cx_{mean}	-0.40	-0.33	0.70*	0.79**	0.46	0,57
	Cx_{SD}	0.31	0.41	0.34	0.33	0.29	0.36

GMFM - Gross Motor Function Measure; Dimension D - "standing"; Dimension E - "walking, running & jumping"; Cx_{mean} - Centroid of motion in the horizontal axis mean; Cx_{SD} - centroid of motion in the horizontal axis standard deviation; Partial correlation – controlling for clothing.

**p<0.01

* p <0.05

Table 7
Mean and 95% confidence interval (CI) of individuals with CP and TD individuals for the motion image variables for video recording 1, 2 & 3, unadjusted and adjusted for clothing

Motion image variable						
	Recording no.	CP		TD		*p*
Not adjusted		Mean	95% CI	Mean	95% CI	
1	Cx_{mean}	62.00	56.3-67.8	55.90	52.9-58.9	0.032
	Cx_{SD}	5.60	3.9-7.2	1.80	1.5-2.1	0.001
2	Cx_{mean}	63.30	57.4-69.2	55.80	53.3-58.3	0.006
	Cx_{SD}	5.30	4.1-6.4	1.90	1.5-2.2	0.001
3	Cx_{mean}	61.60	56.4-66.8	54.30	51.5-57.0	0.007
	Cx_{SD}	5.20	4.2-6.3	2.00	1.5-2.5	0.001
Adjusted						
1	Cx_{mean}	61.6	55.7-67.5	56.1	52.2-60.1	0,181
	Cx_{SD}	4.80	3.7-6.0	2.20	1.4-3.0	0.002
2	Cx_{mean}	63.70	58.2-69.2	55.50	51.2-59.2	0.034
	Cx_{SD}	4.90	3.9-5.8	2.10	1.4-2.7	0.001
3	Cx_{mean}	61.6	56.2-67.1	54.2	50.6-57.9	0.052
	Cx_{SD}	5.0	4.0-6.0	2.1	1.5-2.8	0.001

Cx_{mean} - Centroid of motion in the horizontal axis mean; Cx_{SD} - centroid of motion in the horizontal axis standard deviation; Not adjusted - Student's t-test; Adjusted - Univariate analysis, General Linear Models

Table 8
Mean and 95% confidence interval (CI) of individuals with GMFCS level I and II+III and TD individuals for the motion image variables for video recording 1, 2 & 3, unadjusted and adjusted for clothing.

Motion image variable								
	Recording no.	GMFCS1		GMFCS 2+3		TD		*p*
Not adjusted		Mean	95% CI	Mean	95% CI	Mean	95% CI	
1	Cx_{mean}	58.8	51.6-66.1	69.3	60.9-77.7	55.9	52.9-58.9	0,009
	Cx_{SD}	6.1	3.7-8.6	4.3	3.1-5.4	1.8	1.5-2.1	0.001
2	Cx_{mean}	59.6	53.0-66.3	71.6	60.8-82.3	55.8	53.3-58.3	0.001
	Cx_{SD}	5.5	3.8-7.2	4.7	2.7-6.7	1.9	1.5-2.2	0.001
3	Cx_{mean}	58.9	52.3-65.6	67.6	59.0-76.1	54.3	51.5-57.0	0,004
	Cx_{SD}	5.7	4.3-7.1	4.2	2.9-5.5	2.0	1.5-2.5	0.001
Adjusted								
1	Cx_{mean}	59.1	53.0-65.1	69.6	60.5-78.8	55.7	52.0-59.5	0.039
	Cx_{SD}	5.4	4.2-6.6	3.1	1.3-4.9	2.3	1.5-3.0	0.001
2	Cx_{mean}	60.7	55.4-66.1	73.3	65.2-81.5	55.1	51.8-58.4	0,002
	Cx_{SD}	5.1	4.1-6.2	4.1	2.5-5.6	2.1	1.5-2.8	0.001
3	Cx_{mean}	59.5	53.9-65.1	68.4	59.9-77.0	53.9	50.4-57.4	0.022
	Cx_{SD}	5.4	4.4-6.4	3.7	2.2-5.3	2.2	1.5-2.8	0.001

Cx_{mean} - Centroid of motion in the horizontal axis mean; Cx_{SD} - centroid of motion in the horizontal axis standard deviation; Not adjusted - Student's t-test; Adjusted - Univariate analysis, General Linear Models.