Title

Selective dorsal rhizotomy improves muscle forces during walking in children with spastic cerebral palsy

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Abstract

Background

Selective dorsal rhizotomy aims to reduce spasticity in children with cerebral palsy. Early investigations indicated postoperative weakness, whereas more recent studies showed that selective dorsal rhizotomy either does not change or improves muscle strength. All previous studies assessed muscle strength in a static position, which did not represent the walking situation. The aim of this study was to analyze the influence of selective dorsal rhizotomy on muscle forces during gait.

Methods

Motion capture data of 25 children with spastic cerebral palsy and 10 typically developing participants were collected. A musculoskeletal OpenSim model was used to calculate joint kinematics, joint kinetics and muscle forces during gait. Static optimization and an electromyography-informed approach to calculate muscle forces were compared. A Muscle-Force-Profile was introduced and used to compare the muscle forces during walking before and after a selective dorsal rhizotomy.

Findings

Independent of the approach used (electromyography-informed versus static optimization), selective dorsal rhizotomy significantly normalized forces in spastic muscles during walking and did not reduce the contribution of non-spastic muscles.

Interpretation

This study showed that selective dorsal rhizotomy improves dynamic muscle forces in children with cerebral palsy and leads to less gait pathology, as shown in the improvement in joint kinematics and joint kinetics. Individual muscle force analyses using the Muscle-Force-Profile extend standard joint kinematics and joint moment analyses, which might improve clinical-decision making in children with cerebral palsy in the future. The reference data of our participants and MATLAB code for the Muscle-Force-Profile are publicly available as appendix to this paper.

1. Introduction

Clinical interventions to improve walking in children with cerebral palsy (CP) aim to normalize muscle functions by reducing spasticity, lengthening muscles and/or correcting lever-arms (Schwartz et al., 2004). Bony corrective surgeries, e.g. derotation osteotomies of the femur and tibia, are an efficient way to correct the lever-arms and improve walking in children with CP (Boyer et al., 2016; Carty et al., 2014). Selective dorsal rhizotomy (SDR) is a way to treat spasticity in children with CP by permanently reducing the excitation level of the alpha motor neurons. SDR has been shown to reduce lower limb spasticity, increase range-of-motion of lower limb joints and to improve Gross Motor Function Classification System (GMFCS) levels (Langerak et al., 2012; Munger et al., 2017; Steinbok, 2007).

The impact of SDR on muscle forces in children with CP has, however, been discussed controversially in the clinical and research community. Early investigation regarding changes in muscle strength due to SDR indicated postoperative weakness (Arens et al., 1989; Peacock and Staudt, 1991), whereas more recent studies using instrumented strength measurements showed that SDR either does not change or increases lower limb strength (Engsberg et al., 2002, 1998). Changes in the surgical and rehabilitation procedures, e.g. more selective or conservative approach in cutting the rootlets, as well as using a subjective versus an instrumented objective way to estimate muscle strength might explain the contradicting findings between the early and more recent investigations. Nevertheless, all of these studies assessed muscle strength in an experimental static position, which did not represent the dynamic walking situation. It is, therefore, unclear how the observed changes in isometrically measured muscle strength relate to alterations in muscle force production during gait after an SDR.

Non-invasive, in-vivo measurements of muscle forces during walking are not possible due to technical reasons but gait analysis together with a musculoskeletal model and dynamic simulations can be used to estimate individual muscle forces (Delp et al., 2007). Musculoskeletal modelling has been used previously in children with CP to answer a large variety of research questions, including studies evaluating the effect of strength training on gait kinematics (Damiano et al., 2010), the impact of crouch gait on joint contact forces (Steele et al., 2012), and the effect of muscle transfer surgery on balance recovery (Mansouri et al., 2016). However, to the authors' knowledge, the impact of SDR on functional muscle strength,

i.e. muscle forces during walking, has not been evaluated and, therefore, was the aim of this study. Previous research showed that SDR reduced spasticity in children with CP (Steinbok, 2007). Hence, we hypothesized that SDR decreases forces of spastic muscles during walking and therefore leads to a closer to typically developing gait pattern. Furthermore, we hypothesized that SDR does not deteriorate non-spastic muscles forces during walking.

2. Methods

2.1. Participants

Retrospective motion capture data of 25 children with spastic CP (12/13 girls/boys, mean age: 9.8 (SD 2.1) years, mean weight: 29.9 (SD 5.3) kg, mean height: 1.35 (SD 0.12) m, pre SDR GMFCS scores: I 10 children, II 14 children, unknown 1 child) and 10 typically developing (TD) participants (4/6 girls/boys, mean age: 9.2 (SD 2.8) years, mean weight: 32.8 (SD 15.0) kg, mean height: 1.35 (SD 0.15) m) were included in this study. The data was collected between 1996 and 2006. Twelve participants with CP received bony corrective surgeries before SDR, including bilateral (n=11) and unilateral (n=1) femoral derotation osteotomies, and bilateral (n=3) and unilateral (n=3) tibial derotation osteotomies. One participant received a hip surgery due to septic arthritis eleven years prior to an SDR, one participant received bilateral psoas, hamstrings and gastrocnemius lengthening five years prior to SDR, and one participant received a gastrocnemius lengthening and calcaneal opening wedge osteotomy to correct foot position on the right leg two years prior to SDR. Ten participants with CP received SDR without any prior orthopedic surgery. Detailed information of the CP participants, including isometric muscle strength and spasticity scores from the clinical examinations, can be found in Table 1. Ethics approval was obtained from the ethics committee of the University Hospital Leuven.

2.2. Selective dorsal rhizotomy

Indication for SDR was the presence of spasticity for most lower limb muscles (involvement of muscles at the hip, knee and ankle joint), and sufficient lower limb muscle strength and selectivity. Sufficient lower limb muscle strength and selectivity was judged based on the child's ability to independently come from a squatting to a standing position. To ensure a proper selection of rootlets, electromyography (EMG) of 14 lower limb and sphincter muscles was recorded during SDR. Based on the EMG response, on average 22 (SD 5) % of the sensory rootlets of L1

to S1 were cut. The SDR was always followed by a period of intensive rehabilitation, including 10 hours of physiotherapy per week for the first 3 months and 5 hours of physiotherapy per week until 6 months after the SDR.

2.3. Motion capture

The Vicon Plug-in-Gait marker set for lower limbs, which is an implementation of the Helen Hayes marker set (Kadaba et al., 1990), was placed on each participant. Marker trajectories and ground reaction forces of one static and at least three walking trials at a self-selected walking speed were collected with a 10-15 camera motion capture system (Vicon Motion Systems, Oxford, UK) and two force plates (AMTI, Watertown, MA, USA). Simultaneously, EMG data of following lower limb muscles were collected using a 16 channel EMG- system (Zerowire, Cometa, Italy): left and right rectus femoris, vastus lateralis, biceps femoris, semitendinosus, tibialis anterior, medial gastrocnemius, soleus and gluteus medius. In participants with CP, motion capture data was collected approximately two months before (mean 53 (SD 43) days) and one year after (mean 410 (SD 87) days) SDR.

2.4. Clinical muscle strength and spasticity assessment

Clinical examination of muscle strength (detailed information in the supplementary documents) and spasticity was obtained from each CP child at each motion capture session. Muscle strength was quantified using manual muscle testing in combination with the Medical Research Council (MRC) score (Florence et al., 1992) and spasticity was quantified with the Modified Ashworth Score (Bohannon and Smith, 1987). Experienced physiotherapists did the muscle strength and spasticity assessment. Muscle strength in the context of this manuscript refers to the clinically measured isometric muscle strength quantified with the MRC score, whereas muscle forces refer to the dynamic muscle forces during gait obtained with the musculoskeletal simulations, as described below.

2.5. Musculoskeletal modelling

The generic 'gait2392' OpenSim model (Delp et al., 1990) was scaled to each participant's anthropometry using scale factors derived from surface marker locations and calculated joint centers (Kainz et al., 2017b). The subtalar joint was locked due to insufficient number of surface markers at the foot to track both, the talocrural and subtalar, degrees of freedom. Joint angles during walking were calculated using a Kalman smoother (De Groote et al., 2008)

and joint moments were calculated via inverse dynamics using OpenSim 3.3 (Delp et al., 2007). Muscle forces during gait were calculated using the following two approaches.

2.5.1. Static optimization

Static optimization (SO) minimizes the sum of squared muscle activations and is a common way to calculate muscle forces in OpenSim (Kainz et al., 2018; Wesseling et al., 2016). This approach under consideration of the physiological force-length-velocity relationship was used for all our CP and TD participants.

2.5.2. EMG-informed approach

Static optimization assumes identical neuromuscular control strategies across individuals, which might not be appropriate for children with CP. Hence, an EMG-informed neuromusculoskeletal modelling approach (Lloyd and Besier, 2003; Lloyd and Buchanan, 1996; Thelen et al., 1994) was used to investigate if the inclusion of EMG signals in the estimation of muscle forces would lead to different conclusions compared to the static optimization approach. This approach was only used in a sub-group of our participants (8 children with CP, 10 TD participants) because not all participants with CP had useful EMG signals from both, the pre- and post-SDR, data collection sessions. The quality/usefulness of the EMG signals were judged based on the visual assessment of two experienced researchers (HK and HH).

EMG signals were band-pass filtered (30–300 Hz), full-wave rectified, and low-pass filtered (6 Hz), and subsequently amplitude-normalised to their maximum values obtained from the walking trials. The resulting EMG linear envelopes were used as inputs to the EMG-informed modelling pipeline (Sartori et al., 2014).

As done in previous studies (Hoang et al., 2018; Lloyd and Besier, 2003), a calibration was performed in CEINMS (Pizzolato et al., 2015) using two walking trials to tune the neuromuscular parameters (i.e., tendon slack length, optimal fibre length, maximum isometric force, non-linear shape factor, and EMG-to-activation recursive filter coefficients). The 16 EMG signals were distributed to the corresponding muscle-tendon units of the lower limb. A static optimization approach was used to estimate muscle excitations for muscles that did not have EMG signals (Sartori et al., 2012). In CEINMS, the calibrated neuromusculoskeletal model was used to calculate muscle forces on the remaining walking trials.

2.6. Muscle-Force-Profile (MFP) and Muscle-Profile-Score (MPS)

Similar to the Movement-Analysis-Profile (Baker et al., 2009), a Muscle-Force-Profile (MFP) was introduced and used to compare the pre- and post-SDR muscle forces during walking. The MFP was based on the root-mean-square difference between each CP child's lower limb muscle force waveform normalized to body weight and the average waveform of the TD children. For each analyzed muscle, the root-mean-square difference between the CP child's waveform and the average TD waveform was calculated and divided into positive (CP muscle force is higher than the TD muscle force) and negative parts (CP muscle force is lower than the TD muscle force). The positive and negative Individual-Muscle-Score was the root-mean-square difference multiplied with a scale factor, which represented the percentage of the difference for which the score was respectively positive and negative. For example, if the CP child's muscle force was below the TD muscle force for 40% of the root-mean-square difference, the negative scale factor was -0.4 and the positive scale factor was 0.6. Due to the scale factor, the sum of the absolute values of the negative and positive parts of the Individual-Muscle-Score was equal to the root-mean-square difference between the CP child's muscle force waveform and the average waveform of the TD children. The mean of the root-mean-square differences between the CP and average TD muscle force waveforms over all analyzed individual muscles was the Muscle-Profile-Score (MPS). The MFP is a graphical illustration of the Individual-Muscle-Score and the MPS. Depending on the research question, a sub-selection or the Individual-Muscle-Score of all muscles can be plotted as the MFP as illustrated in Fig. 2. An improvement in muscle forces due to an intervention would lead to a smaller MFP (less deviation to TD muscle forces).

For the purpose of the current study, two MPS were calculated. One for spastic and one for non-spastic muscles. The MPS for spastic muscles included the Individual-Muscle-Score of the hamstring muscles, the medial and lateral gastrocnemius, soleus, psoas, iliacus, adductor muscles, tibialis posterior and rectus femoris. These spastic muscles were chosen based on the clinical spasticity assessment. The MPS for non-spastic muscles included the Individual-Muscle-Score of the gluteus maximus and medius, tibialis anterior, vastus medialis, vastus lateralis and vastus intermedius. The non-spastic muscles were selected muscles, which are important for achieving an upright pose.

2.7. Data analysis

All data were normalized to 100% of the gait cycle. Joint moments and muscle forces were additionally normalized to body mass. The average waveforms from three left and three right trials of each participant were used for all analyses. The MPS for spastic and non-spastic muscles was calculated for each child's pre- and post-SDR gait pattern. Furthermore, similar to the Gait-Profile-Score (Baker et al., 2009), pre- and post-SDR joint kinematic and kinetic deviations from the TD children were calculated. The right and left leg of each child were analyzed separately as the SDR was tailored to each individual leg, which led to 50 individually analyzed limbs. Not all of our data was normally distributed. Hence, to investigate if SDR lead to closer to TD gait patterns and muscle forces, we compared pre- with post-SDR deviations in muscle forces (spastic and non-spastic MPS), joint kinetics and joint kinematics using non-parametric Wilcoxon signed-rank tests. Furthermore, we compared pre- with post-SDR muscle strength and spasticity scores from the clinical examinations using non-parametric Wilcoxon signed-rank tests. We assessed if there were significant difference in age, height, body weight and body mass index between the TD participant group and the pre-, as well as, post-SDR group using non-parametric Mann-Whitney U-test. The significance level was $P < 0.05$ and IBM SPSS Statistics 24 (IBM Corporation, New York, USA) was used for all statistical analyses.

3. Results

No significant difference in age, height, body weight and body mass index between the TD participant group and the pre-, as well as, post-SDR group was observed.

SDR improved muscle forces during gait, as evident in the significantly decreased muscle force deviations from the TD muscle forces (Fig. 1 and 2). The spastic MPS significantly decreased ($P < 0.001$) from a mean of 1.56 (SD 0.58) N/kg to a mean of 1.19 (SD 0.52) N/kg, indicating that SDR successfully normalized forces in these muscles during gait. Non-spastic muscle forces during gait showed a significant improvement ($P < 0.001$) from a mean MPS of 1.09 (SD 0.45) N/kg to a mean of 0.73 (SD 0.41) N/kg (Fig. 2). Including the Individual-Muscle-Score from all muscles, overall muscle forces improved significantly ($P < 0.001$) from a mean of 1.58 (SD 0.49) N/kg before the SDR to a mean of 1.13 (SD 0.44) N/kg after the SDR (Fig. 3).

Using the EMG-informed approach instead of static optimization to estimate muscle forces changed the dynamic muscle forces of several muscles and therefore the Individual-Muscle-Scores but had a minor impact on the overall MPS for spastic and non-spastic muscles (Fig. 4 and 5). Changes in MPS between the pre- and post-SDR gait assessment were not significantly different between both approaches.

SDR improved joint kinematics and kinetics, as evident in the significantly ($P<0.05$) decreased deviations from the TD participants (Fig. 3). Joint kinematic deviations significantly improved ($P=0.025$) from a mean of 9.27 (SD 2.47) degrees to a mean of 8.08 (SD 2.36) degrees, and joint kinetic deviations significantly improved ($P=0.001$) from a mean of 0.27 (SD 0.17) Nm/kg to a mean of 0.19 (SD 0.14) Nm/kg.

Clinical examinations showed an improvement after the SDR. Spasticity scores of all analyzed muscles and all muscle strength scores, except for the hip flexor muscle group, significantly ($P<0.05$) improved from the pre- to the post-SDR examinations (Table 1).

4. Discussion

To the best of our knowledge, this was the first study, which analyzed muscle force production during gait before and after SDR. The findings of our study are unique for the following reasons: First, we showed that SDR normalizes spastic muscle forces during walking in children with CP. Furthermore, our results showed that SDR does also normalize non-spastic muscles forces during gait. These findings confirmed our hypothesis and highlighted that SDR leads to closer to TD dynamic muscle forces in agreement with the reduction of gait pathology as evident in the decreased deviation in joint kinematics and kinetics after the SDR compared to before the SDR. Using an EMG-informed approach to calculate muscle forces did not change this conclusion of our study. However, individual muscle forces did show differences between the SO and EMG-informed approach.

The findings from the clinical examinations showed that, as expected, spasticity significantly decreased after SDR, which is in agreement with previous studies (Ailon et al., 2015; McLaughlin et al., 2002; Munger et al., 2017). In contrast to early investigations, which showed that SDR leads to postoperative weakness (Arens et al., 1989; Peacock and Staudt, 1991), our results from the clinical examinations showed a small (mean 0.2 (SD 0.3)

improvement in MRC scores over all muscles) but significant increase in isometric muscle strength in most muscles after the SDR. In these early studies, it was quite common to cut 25% to 50% of the rootlets, whereas in our patient population only 15% to 30% of the rootlets were cut very selectively. The discrepancy in the percentage of sacrificed rootlets and the intensive rehabilitation could be reasons for the observed differences between earlier studies and our results. More recent studies including instrumented strength measurements showed that SDR either does not change or improves lower limb strength (Engsberg et al., 2002, 1998), which is in agreement with our findings. However, clinical examinations of muscle strength are based on maximum voluntary contractions in a static position and, therefore, do not represent the muscle force capacity during walking. Walking requires sub-maximal dynamic muscle forces, which are difficult to measure in an experimental setup. Our results from the clinical isometric strength measurements showed a similar increase in muscle strength over all analyzed muscle groups, whereas the MFP showed large difference in the improvement in dynamic muscles forces between individual muscles. For example, muscles deviating more before the SDR (e.g. quadriceps muscles) improved more after the SDR compared to muscles that only deviated slightly before the SDR (e.g. adductor or gluteus muscles).

Furthermore, for the knee extensors, the improved muscle strength in the clinical (static) measurement is difficult to link to the improvement in gait function. Clinically measured knee extensor muscle strength significantly increased after the SDR. The improvement of the dynamic quadriceps muscle forces, however, was achieved by decreasing muscle forces during gait. Hence, it is questionable how relevant clinically measured isometric muscle strength is for dynamic movements like walking. Furthermore, clinical muscle strength measurements quantified with the MRC scale are known to have poor reliability (Mahony et al., 2009). Flexed knee gait is known to require higher quadriceps forces compared to TD gait (Steele et al., 2010). The observed decrease in quadriceps muscle forces during walking after the SDR were likely caused by decreased spasticity of the hamstring muscles, which led to normalized (decreased) hamstring muscles forces as shown in the MFP, and therefore reduced the flexed knee gait pattern. The observed improvement in gait was explained by a decrease of muscle forces that were abnormally high before the treatment, highlighting that isometric strength measurements by themselves do not fully capture the successfulness of an intervention in terms of normalization of muscle force during gait.

The impact of the modelling approach (EMG-informed versus static optimization) on the overall MPS was minor and did not change the conclusion of this study. However, using the EMG-informed approach instead of static optimization led, as expected, to different muscle force waveforms and, therefore, to different Individual-Muscle-Scores (Fig. 4 and 5). Differences in muscle forces between both approaches were observed in our CP and TD participants. The amount of difference depended on the analyzed muscle. Before the SDR the hamstring, soleus and gastrocnemius muscles of all our CP participants were spastic with a Modified Ashworth Score of one or above (Table 1, supplementary Fig. S1). During the pre-SDR gait assessment the hamstring and soleus muscles forces of our CP participants were above the TD participants, whereas the gastrocnemius muscle forces were below the TD values when using static optimization and above the TD values when using the EMG-informed approach (Fig. 5). It, therefore, seems that the inclusion of EMG signals, especially from spastic muscles, can have a big impact on the estimation of muscle forces. Researchers and clinicians interested in individual muscle forces should, therefore, be aware that static optimization will lead to different muscle forces compared to an EMG-informed approach.

Musculoskeletal simulations extend standard joint kinematics and net joint moment analyses. For example, by only looking at the joint moments it would be impossible to differentiate which muscles generate pathological muscle forces. From the pre-SDR ankle dorsi-/plantarflexion moments it was not possible to reason which of the plantarflexor muscles were below or above the TD values. The MFP can further be used to indicate which muscles would benefit from a strength training. In our participants with CP, the dynamic quadriceps muscles forces were above the TD values, which indicates that strengthening the quadriceps would very unlikely improve their gait pattern. On the other hand, the tibialis posterior muscle forces were below the TD values and, therefore, strengthening this muscle might improve their gait pattern. These conclusions would not have been possible without the inclusion of musculoskeletal modelling in the gait assessment.

We introduced the MFP and MPS to analyze and summarize pathological muscle force deviations to TD muscle functions during gait. The MFP was considered as a tool to analyze individual muscles (e.g. during clinical gait analysis), whereas the advantage of the MPS is to have an overall score for muscle force deviations, which is useful for statistical analysis in

intervention studies as shown in this paper. The reference data and MATLAB code for the MFP and MPS are publicly available as electronic appendix to this paper.

Our participants with CP were quite heterogeneous at the time of the SDR. Participants differed in GMFCS level and orthopedic surgery history. Secondary analyses did not show any significant differences in the improvement in the MPS between children with a GMFCS level of I or II, and children who prior to SDR did or did not receive bony surgeries to correct lever arms. It, therefore, seems that the improvement in muscle forces during gait is independent of the child's GMFCS level and orthopedic surgery history.

This study has some limitations. First, we used scaled generic models, which did not include subject-specific bony deformities, to calculate muscle forces. Previous comparisons between scaled-generic and medical-imaging based models showed similar muscle functions in children with CP (Correa et al., 2011) and, therefore, we expect to see similar results with medical-imaging based models. Second, gait kinematics and gait kinetics in children with CP is usually calculated with the conventional gait model, whereas we used a musculoskeletal OpenSim model. Recent research, however, showed that musculoskeletal models are at least as reliable as the conventional gait model and, therefore, suitable for clinical gait analysis (Kainz et al., 2017a). Third, a control group of matched CP children who did not receive an SDR was not available for this study. Considering that gait pathologies usually increase with age in CP, we are confident that SDR had a positive impact on the children's gait ability.

5. Conclusions

In conclusion, our results showed that the improvement in joint kinematics and kinetics after SDR are associated with a normalization in spastic and non-spastic muscles forces during walking in children with CP, independent of the muscle force calculation approach. The MFP and MPS were introduced to analyze and summarize pathological muscle force deviations to TD muscle functions during gait. Individual muscle force analyses using the MPS extend standard joint kinematics and net joint moment analyses. Considering that muscles are anatomical structures that are often corrected during therapeutic and orthopedic interventions, providing additional data on individual muscle forces to identify

366 musculoskeletal causes of dysfunction may improve clinical decision-making in children with
367 CP.

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Table 1. Detailed information (mean (SD)) of the participants with CP including clinical spasticity and isometric muscle strength measurement results. Spasticity was graded with the Modified Ashworth Scale. Muscle strength was quantified using the Medical Research Council (MRC) scale. ***, **, * = significant improvement from pre- to post-SDR examination with p values of $P < 0.001$, $P < 0.01$, and $P < 0.05$, respectively; ¹ = pre SDR spasticity scores of three limbs were not available for the tibialis posterior muscle; ² = pre SDR MRC scores of two limbs were not available for the ankle plantar-flexor muscle group.

General information	Pre-SDR	Post-SDR
Age [years]	10 (SD 2)	11 (SD 2)
Weight [kilogram]	30 (SD 5)	35(SD 6)
Height [meters]	1.3 (SD 0.1)	1.4 (SD 0.1)
Gender [female/male]	12 / 13	
Gait velocity [meters/seconds]	1.07 (SD 0.15)	0.98 (SD 0.18)
Spasticity [Modified Ashworth Scale score / number of limbs]		
Hip flexors	0/9, 1/27, 1.5/11, 2/3	0/31, 0.5/2, 1/14, 1.5/3 ***
Hip adductors	0/6, 0.5/1, 1/11, 1.5/18, 2/14	0/28, 1/20, 1.5/2 ***
Hamstrings	1/2, 1.5/22, 2/22, 3/4	0/13, 0.5/1, 1/23, 1.5/12, 2/1 ***
Soleus	1/20, 1.5/24, 2/6	0/28, 1/13, 1.5/9 ***
Gastrocnemius	1/2, 1.5/18, 2/26, 3/4	0/10, 1/22, 1.5/11, 2/7 ***
Tibialis posterior ¹	0/30, 1/14, 1.5/3	0/50 ***
Muscle strength [MRC scores / number of limbs]		
Hip flexion	3.5/16, 4/32, 5/2	3/2, 3.5/8, 4/38, 5/2
Hip extension	2.5/4, 3/4, 3.5/18, 4/23, 5/1	3/2, 3.5/14, 4/34 **
Hip abduction	2.5/3, 3/12, 3.5/18, 4/17	2.5/1, 3/2, 3.5/26, 4/19, 5/2 **
Hip adduction	3/2, 3.5/9, 4/34, 5/5	3.5/4, 4/35, 5/11 *
Knee flexion	3/2, 3.5/33, 4/14, 5/1	3/2, 3.5/21, 4/22, 5/5 **
Knee extension	3.5/16, 4/33, 5/1	3.5/2, 4/37, 5/11 ***
Ankle dorsi-flexion	2.5/6, 3/3, 3.5/19, 4/21, 5/1	1.5/1, 3/4, 3.5/12, 4/25, 5/8 ***

Ankle plantar-flexion ²	1.5/1, 2.5/7, 3/3, 3.5/25, 4/12	2.5/5, 3/5, 3.5/20, 4/20 *
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Fig. 1. Pre- and post-SDR waveform from a selection of muscle forces. The grey area represents the average plus/minus standard deviation of the muscle force waveforms from the typically developing (TD) participants. The red and green waveforms represent the average pre- and post-SDR muscle forces from the children with CP. The adductor muscles, i.e. adductor longus, brevis and magnus, were summarized to one waveform.

Fig. 2. The average pre- (red bars) and post-SDR (green bars) Muscle-Force-Profile for all participants with CP. Positive and negative Individual-Muscle-Score for a selection of usually spastic muscles (semimembranosus to rectus femoris) and non-spastic muscles (gluteus maximus to vastus

intermedius), as well as the Muscle-Profile-Score (MPS) for spastic and non-spastic muscles are shown. Black boxes represent the average variation observed in typically developing (TD) children. The closer the bars are to the black boxes, the smaller are the deviations from the TD muscle forces. If the bars are within the black boxes, it indicates that the deviation of the CP children was less than the variation observed in the TD children. The adductor muscles, i.e. adductor longus, brevis and magnus, were summarized to one bar.

Fig. 3. The effect of SDR on differences in joint kinematic, joint kinetics and muscle forces between CP and TD participants during walking. Error bars represent the standard error of the mean.

Fig. 4. Pre- and post-SDR waveform from a selection of muscle forces calculated with static optimization (SO, dashed lines) and the EMG-informed approach (solid lines) for a sub-group of 8 participants with CP and 10 TD participants. The grey area represents the average plus/minus standard deviation of the muscle force waveforms from the typically developing (TD) participants. The red and green waveforms represent the average

pre- and post-SDR muscle forces from the children with CP. The adductor muscles, i.e. adductor longus, brevis and magnus, were summarized to one waveform.

Fig. 5. The average pre- (red bars) and post-SDR (green bars) Muscle-Force-Profile for a sub-group of 8 participants with CP obtained with static optimization (top graph) and the EMG-informed approach (bottom graph). Positive and negative Individual-Muscle-Score for a selection of usually

spastic muscles (semimembranosus to rectus femoris) and non-spastic muscles (gluteus maximus to vastus intermedius), as well as the Muscle-Profile-Score (MPS) for spastic and non-spastic muscles are shown. Black boxes represent the average variation observed in typically developing (TD) children. The closer the bars are to the black boxes, the smaller are the deviations from the TD muscle forces. If the bars are within the black boxes, it indicates that the deviation of the CP children was less than the variation observed in the TD children. The adductor muscles, i.e. adductor longus, brevis and magnus, were summarized to one bar. The grey dotted boxes highlight the similarity between the overall MPS obtained with static optimization and the EMG-informed approach.