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# Do dynamic and static clinical measurements correlate with gait analysis parameters in children with cerebral palsy?

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**Abstract**

The present study documents the correlation between gait analysis data and clinical measurements and evaluates the combined predictive value of static and dynamic clinical measurements on gait data of children with cerebral palsy. Two hundred patients were evaluated using a set of measurements of range of motion (ROM), alignment, spasticity, strength and selectivity, and by three-dimensional gait analysis. Fair to moderate correlations were found between clinical measurements and gait data, the overall highest correlation being 0.60. Clinical data of strength and selectivity had the highest degree of significant correlations with gait data, compared to the ROM and spasticity. ROM, spasticity and strength measurements for the hip in the coronal plane and spasticity of rectus femoris most frequently showed fair to moderate correlations to gait data. Time and distance and EMG parameters mainly correlated with strength and selectivity parameters. Unexpectedly, alignment parameters only fairly correlated with hip rotation in stance. Multiple regression analysis revealed that adding dynamic clinical measurements (spasticity, strength and selectivity) to a static model (ROM) enhanced the link between clinical measurements and gait data. The variance of gait parameters was better explained by a combined model of static and dynamic clinical measurements, compared to a purely static model. However, $R^2$-values were low. Gait analysis data cannot be sufficiently predicted by a combination of clinical measurements. The independence of the measurements supports the notion that both, clinical examination and gait analysis data provide important information for delineating the problems of children with CP.


*Keywords:* Gait; Clinical measurements; CP; Correlation; Multiple regression

## 1. Introduction

The effective management of gait problems associated with cerebral palsy (CP) requires detailed examination to guide decisions on treatment strategies [1–7]. Both gait analysis and clinical measurements are critical factors in the evaluation and treatment of gait disorders in children with CP. Clinical assessment includes the measurement of primary and secondary motor impairments such as range of motion (ROM) [5], spasticity [2,8–10], muscle strength, selective motor control [2,10], pain [1], etc.

Unfortunately, among some clinicians, the clinical examination is still believed to provide sufficient information to define the treatment in children with CP. However, DeLuca et al. [11] reported that computerized gait analysis information modified the surgical treatment recommendations made by experienced physicians for the patient with CP in about half (52%) of the patients evaluated. Gait analysis is usually combined with a clinical examination and studies often include both dynamic gait data and clinical assessment in order to report on the effect of several treatment methods [1,3,10]. However, scientific evidence on the benefits of three-dimensional gait analysis in addition to

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clinical examination is still insufficient. The present study therefore focuses on the relationship between clinical measurements and gait analysis data.

Damiano and Abel [13] reported a moderate to good relationship between the mean strength in the lower limb muscles and the gait parameters of velocity and cadence in 11 patients with spastic CP ($r$-values 0.63 and 0.71, respectively). In a previous study by Damiano and Abel [12], quantitative gait analysis data such as cadence, velocity, stride length and sagittal hip and knee excursion were found to be significantly correlated with the Gross Motor Function Measure score, for a group of 32 children with CP. $R$-values ranged between 0.49 and 0.79. In a retrospective report on 22 patients with CP, Aktas et al. [15] found physical examination data of thigh–foot angle and trans-malleolar axis to be correlated with dynamic gait data of tibial rotation and also to be good predictors of tibial rotation during gait. $R^2$-values were 0.61 and 0.65, respectively. In contrast to previous studies, Orendurff et al. [14] found clinical measurements of ROM to be poorly correlated with gait analysis parameters ($R^2$-values $< 0.30$) for 106 children with CP. Also a recent study by McMulkin et al. [6] in 80 patients with CP and 30 normal subjects, reported that clinical examination measurements of ROM had poor correlation with data of gait analysis and as such were poor predictors of dynamic gait ($r$-values $< 0.50$ and $R^2$-values $< 0.30$).

Previous studies only correlated a few clinical parameters to some gait analysis variables. There has been no systematic study on the relationship between the complete set of commonly assessed clinical parameters (ROM, spasticity, strength and selectivity) and gait analysis parameters (kinetics, kinematics, EMG and time and distance parameters). The majority of the studies only include (static) ROM measurements. It was hypothesised that, due to the dynamic character of gait, clinical measurements of spasticity, strength and selectivity would show a higher relationship with gait data than static ROM measurements. Therefore, a study was set up to assess the correlation between objective gait analysis data and a full set of clinical parameters (including ROM, spasticity, strength and selectivity) and to evaluate the combined predictive value of static and dynamic clinical measurements on gait data for a large group of children with CP.

## 2. Methods

### 2.1. Subjects

Two hundred children with cerebral palsy (112 with diplegia and 88 with hemiplegia) were included in the study. The children were taken from the database of the clinical motion analysis laboratory, by randomly selecting 25 patients (14 with diplegia and 11 with hemiplegia) in eight age groups (from 4 to 11 years). The inclusion criteria were (a) a diagnosis of predominantly spastic type of CP, (b) ambulatory status, without assistive devices, (c) patient age between 4 and 12 years, (d) sufficient cooperation for an accurate full clinical assessment and three-dimensional gait analysis, and (e) no surgery within 18 months and no serial casting or botulinum toxin A treatment 6 months before the evaluation time. Detailed information on the subject cohort can be found in Table 1. The mean age of the total group was 8.0 years with a range of 4.2–12.0 years. The children received 1–7 physical therapy sessions per week, with a mean duration of 43(±14) min. Apart from physical therapy, day and night orthoses were used by 61% and 49% of the patients, respectively. Seventy-three children received at least one session of serial casting for the lower limbs at a younger age, and 113 patients were previously treated with botulinum toxin A (53 patients once, 36 patients twice and 24 patients more than two times). Of the 200 patients, 18 had previous surgery on the lower extremities including Achilles tendon lengthening (for 10 patients), soft-tissue releases (for 5 patients), or soft-tissue releases with bony procedures (for 3 patients).

### 2.2. Data collection and analysis

All patients were examined by three-dimensional gait analysis followed by a standardized clinical examination.

Table 1
Patient characteristics

| | |
|---|---|
| Number of patients | 200 |
| Diagnosis | 112 diplegia, 88 hemiplegia |
| Age | |
| Mean (S.D.) | 8.06 years (S.D. = 2.36) |
| Minimum age | 4 years 2.5 months |
| Maximum age | 12 years 0 months |
| Physical therapy (PT) | |
| PT sessions (median) | 3 sessions/week (range 1–7) |
| Mean duration of PT session | 43 min (S.D. = 14 min) |
| Limited PT (<2 sessions/week) | 13.5% (27/200) |
| Intensive PT (≥2 sessions/week) | 86.5% (173/200) |
| Use of day orthoses | |
| Not used | 39% (78/200) |
| Not frequently used (<50% of the day) | 4.5% (9/200) |
| Intensively used (>50% of the day) | 56.5% (113/200) |
| Use of night orthoses | |
| No night orthoses | 51% (102/200) |
| Not frequently used (<25% of the night) | 10.5% (21/200) |
| Intensively used (>25% of the night) | 38.5% (77/200) |
| Clinical history | |
| Achilles tendon lengthening | 5% (10/200) |
| Soft-tissue surgery | 4% (4/200) |
| Soft-tissue surgery with bony procedure | 1.5% (3/200) |
| 1 session of botulinum toxine A treatment | 26.5% (53/200) |
| 2 sessions of botulinum toxine A treatment | 18% (36/200) |
| >2 sessions of botulinum toxine A treatment | 12% (24/200) |
| Serial casting (at least one session) | 36.5% (73/200) |

Kinematic and kinetic measurements were collected using a six-camera VICON system (612 data-capturing system, with lower limb PluginGait marker set, VICON, Oxford Metrics, Oxford, UK), and two AMTI force plates (Advanced Mechanical Technology Inc., Watertown, MA). The subject was asked to walk at comfortable speed down the 10 m walkway. Data were collected in the course of three successful trials. Surface EMG data were collected on seven lower extremity muscle groups, using a 16 channel K-lab EMG system (Biometrics Europe, The Netherlands). Outputs of the rectus femoris, vastus lateralis, medial and lateral hamstrings, tibialis anterior, gastrocnemius and soleus muscles were obtained. The raw EMG signals were high-pass filtered with a cut-off frequency of 20 Hz (18 db/oct, Butterworth application), and also rectified and low-pass filtered to acquire the linear envelopes. Workstation and Polygon software (Oxford Metrics, Oxford, UK) were used to define gait cycles, to determine the time and distance parameters and to estimate the joint angles and internal moments and power.

Gait analysis data were studied by one kinesiologist, who did not know the results of the clinical examination of the children. A set of 49 parameters was selected from the kinematic (joint angles), the kinetic (internal moments and powers) and the EMG (linear envelope and raw EMG) results. All selected gait parameters were defined, based on a study of the literatures [16–18]. The gait parameters were discrete values of joint angles, moment and power at specific points in the gait cycle, which were determined for three randomly selected gait trials per subject, and averaged. Because of lack of independence between left and right sides, only one side was included in the statistical analysis. The selected side was randomly defined. An overview of the gait analysis parameters can be found in the first column of Tables 2–5.

The clinical examination was performed by three well-trained kinesiologists. Clinical examination resulted in 32 parameters, including assessment of ROM, alignment, spasticity, strength and selectivity. ROM measurements at the hip included extension, internal and external rotation and abduction. Hip extension was evaluated by the Thomas test and abduction was evaluated, both with hip and knee flexed and extended [2,7]. At the knee, unilateral and bilateral popliteal angles were evaluated [7]. The ankle ROM measurements included maximal dorsiflexion with knee flexed and extended to differentiate between gastrocnemius and soleus muscle contracture (Silfverskiöld test) [2]. The assessed alignment parameters included femoral anteversion

Table 2
Correlation coefficients between gait analysis data and measurements of ROM in 200 children with cerebral palsy

| Parameters | Hipext | Hipabd0 | Hipabd90 | Hipintrot | Hipextrot | PopAUni | PopABi | Adors90 | Adors0 | FemAnt | TibFemA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time and distance | | | | | | | | | | | |
| Cadence | 0.16* | – | – | – | – | **0.21**** | **0.21**** | – | – | – | – |
| Gait velocity | **0.25***** | **0.31***** | **0.25***** | – | – | – | – | **−0.21**** | −0.19** | – | – |
| Step length | **0.24***** | **0.24***** | – | – | – | – | −0.18* | **−0.23**** | −0.17* | – | – |
| Timing of TO | **−0.29***** | – | **−0.29***** | – | – | −0.14* | – | **0.23**** | **0.24***** | **0.21**** | – |
| Kinematics | | | | | | | | | | | |
| Pelvic mean anterior tilt | −0.14* | – | – | – | – | – | – | – | – | – | – |
| Pelvic range of sagital motion | – | – | – | – | – | – | – | – | – | – | – |
| Pelvic range of coronal motion | – | – | – | – | – | – | – | – | – | – | – |
| Pelvic range of transverse motion | – | – | – | – | – | – | – | – | – | – | – |
| Pelvic mean obliquity angle | – | – | **−0.25***** | – | – | – | – | – | 0.14* | – | – |
| Pelvic mean rotation angle | – | – | **−0.32***** | – | −0.17** | – | – | – | – | – | – |
| Hip angle at terminal ST | **−0.39***** | **−0.30***** | **−0.45***** | – | – | **−0.25***** | −0.14* | – | – | – | 0.15* |
| Hip mean coronal angle in SW | – | – | – | – | – | −0.15* | −0.15* | – | – | – | – |
| Hip rotation angle at IC | **−0.21**** | – | **−0.21**** | **0.28***** | −0.19** | – | – | | | **0.28***** | – |
| Hip rotation angle at TO | **−0.24***** | **−0.21**** | **−0.38***** | **0.30***** | – | – | – | – | – | **0.29***** | – |
| Hip range of sagital motion in ST | **0.25***** | **−0.31***** | **0.29***** | – | – | 0.17* | – | −0.14* | −0.14* | – | **−0.23***** |
| Hip maximal flexion in SW | – | – | – | – | – | – | – | −0.17* | −0.17* | – | – |
| Hip flexion velocity in SW | **0.32***** | – | **0.42***** | – | – | **0.26***** | 0.15* | – | – | – | −0.15* |
| Knee flexion angle at LR | – | – | – | −0.17* | – | – | – | – | – | – | – |
| Knee maximal extension in ST | **−0.28***** | −0.20** | **−0.36***** | – | – | **−0.28***** | −0.18*, | – | – | – | 0.16* |
| Knee timing of maximal flexion in SW | – | – | – | – | – | – | 0.14* | – | – | – | – |

Table 2 (*Continued*)

| Parameters | Hipext | Hipabd0 | Hipabd90 | Hipintrot | Hipextrot | PopAUni | PopABi | Adors90 | Adors0 | FemAnt | TibFemA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Knee maximal flexion in SW | – | – | – | – | – | – | – | – | – | – | – |
| Knee max flexion velocity around TO | **0.40**$^{***}$ | 0.20$^{**}$ | **0.50**$^{***}$ | – | – | **0.26**$^{***}$ | – | – | – | – | – |
| Ankle max dorsiflexion angle at mid ST | – | – | −0.15$^{*}$ | – | – | – | – | **0.37**$^{***}$ | **0.27**$^{***}$ | – | – |
| Ankle range of motion during push off | 0.20$^{**}$ | – | **0.26**$^{***}$ | – | – | – | – | −0.18$^{*}$ | – | – | −0.17$^{*}$ |
| Ankle maximium dorsiflexion in ST | – | – | – | – | – | – | – | **0.50**$^{***}$ | **0.50**$^{***}$ | – | – |
| Ankle timing of max dorsiflexion in ST | – | – | – | – | – | – | – | **0.28**$^{***}$ | **0.28**$^{***}$ | – | – |
| Ankle max plantar flex velocity around TO | **−0.23**$^{**}$ | – | **−0.28**$^{***}$ | – | – | – | – | – | – | – | **0.22**$^{**}$ |
| Foot mean alignment ST | – | – | −0.17$^{*}$ | **0.35**$^{***}$ | – | – | – | – | – | **0.29**$^{***}$ | −0.19$^{***}$ |
| Ankle second rocker | – | – | – | – | – | – | – | −0.20$^{**}$ | **−0.23**$^{***}$ | – | – |
| Ankle double bump in ST | – | – | – | – | – | – | – | – | – | – | – |
| Kinetics | | | | | | | | | | | |
| Hip maximium abduction moment | 0.17$^{*}$ | – | 0.18$^{**}$ | −0.14$^{*}$ | – | – | – | **−0.25**$^{***}$ | **−0.21**$^{**}$ | – | – |
| Hip timing of 0 moment | −0.20$^{**}$ | – | **−0.23**$^{***}$ | – | – | – | – | 0.17$^{*}$ | – | 0.20$^{**}$ | – |
| Hip maximal power generation in ST | – | – | – | – | – | – | – | – | – | – | – |
| Hip maximal power absorption in ST | – | – | – | – | – | – | – | – | 0.15$^{*}$ | – | 0.20$^{**}$ |
| Hip max power generation at TO/preSW | – | – | – | – | – | −0.16$^{*}$ | −0.17$^{*}$ | – | – | – | −0.16$^{*}$ |
| Knee maximal flexion moment in ST | – | – | – | – | – | – | – | – | – | – | – |
| Knee maximal extension moment in ST | **−0.21**$^{**}$ | **−0.26**$^{***}$ | **−0.25**$^{***}$ | – | – | **−0.25**$^{***}$ | −0.17$^{*}$ | – | – | – | – |
| Knee maximal power generation in ST | – | – | – | – | | – | – | – | – | – | – |
| Knee maximal power absorption in ST | – | – | – | −0.14$^{*}$ | – | – | −0.14$^{*}$ | – | – | – | – |
| Ankle peak plantarflex moment preSW | – | – | – | – | – | **−0.22**$^{**}$ | **−0.28**$^{***}$ | – | – | – | – |
| Ankle peak power generated at preSW | **0.22**$^{**}$ | – | 0.14$^{*}$ | −0.19$^{**}$ | – | – | −0.18$^{*}$, | – | – | – | – |
| Ankle peak power absorption at LR | – | – | – | – | – | – | – | **0.43**$^{***}$ | **0.43**$^{***}$ | – | – |
| EMG data | | | | | | | | | | | |
| Medial hamstrings activity pattern | – | – | 0.17$^{*}$ | – | – | – | – | – | – | – | – |
| Lateral hamstrings activity pattern | – | – | 0.14$^{*}$ | – | – | – | – | – | – | – | – |
| Rectus femoris activity pattern in ST | – | **−0.29**$^{***}$ | – | – | – | – | – | – | – | – | – |
| Rectus femoris acivity pattern in SW | – | – | – | – | – | – | – | – | – | – | – |
| Tibialis anterior activity at IC | – | – | – | – | – | – | – | – | – | – | – |
| Gastrocnemius activity at IC | −0.18$^{*}$ | **−0.21**$^{**}$ | −0.16$^{*}$ | – | – | – | – | −0.20$^{**}$ | **−0.25**$^{***}$ | – | – |
| Vastus lateralis activity pattern | – | – | – | – | – | – | – | – | – | – | – |

Hipext: hip extension; Hipabd0: hip abduction (with hip and knee extended); Hipabd90: hip abduction (with hip and knee flexed); Hipintrot: hip internal rotation; Hipextrot: hip external rotation; PopAUni: unilateral popliteal angle; PopAbi: bilateral popliteal angle; Adors90: ankle dorsiflexion with knee flexed; Adors0: ankle dorsiflexion with knee extended; FemAnt: femoral anteversion; TibFemA: tibio-femoral angle; ST: stance; SW: swinq; IC: initial contact; TO: toe off; flex: flexior; max: maximal.

$^{*}$ $p < 0.05$.

$^{**}$ $p < 0.01$.

$^{***}$ $p < 0.001$.

Table 3
Correlation coefficients between gait analysis data and measurements of spasticity in 200 children with cerebral palsy

| Parameters | AshHipfl | AshAd90 | Ashhamstri | Ashgastr | Tardhamstr | Tardgastr | Ashtibpost | DunElly |
|---|---|---|---|---|---|---|---|---|
| Time and distance | | | | | | | | |
| Cadence | – | – | −0.16* | – | – | – | – | – |
| Gait velocity | **−0.21**** | **−0.31***** | – | – | – | −0.19** | – | −0.30*** |
| Step length | −0.18** | **−0.32***** | – | – | – | – | – | **−0.23**** |
| Timing of TO | 0.19** | **0.32***** | – | – | – | 0.20** | – | **0.21**** |
| Kinematics | | | | | | | | |
| Pelvic mean anterior tilt | **0.26***** | 0.19** | – | 0.16* | – | **−0.21**** | 0.14* | **0.26***** |
| Pelvic range of sagital motion | **0.21**** | **0.28***** | **0.29***** | 0.17* | **−0.27***** | – | – | **0.32***** |
| Pelvic range of coronal motion | – | – | – | – | – | – | – | – |
| Pelvic range of transverse motion | 0.15* | – | – | – | – | – | – | – |
| Pelvic mean obliquity angle | – | **0.25***** | – | – | – | – | – | 0.19** |
| Pelvic mean rotation angle | – | **0.27***** | – | – | – | – | – | – |
| Hip angle at terminal ST | **0.39***** | **0.33***** | **0.22**** | – | **−0.21**** | – | – | **0.41***** |
| Hip mean coronal angle in SW | – | – | 0.16* | 0.14* | – | – | – | – |
| Hip rotation angle at IC | **0.28***** | 0.20** | – | – | – | – | – | – |
| Hip rotation angle at TO | **−0.30***** | **0.24***** | – | – | – | – | – | 0.20** |
| Hip range of sagital motion in ST | −0.20** | **−0.21**** | **−0.27***** | – | 0.19** | **−0.23**** | – | **−0.29***** |
| Hip maximal flexion in SW | 0.20** | – | – | **0.21**** | – | **−0.26***** | **0.21**** | – |
| Hip flexion velocity in SW | **−0.27***** | **−0.33***** | **−0.23**** | – | **0.22**** | – | – | **−0.34***** |
| Knee flexion angle at LR | −0.15* | −0.18** | – | −0.19** | – | – | – | −0.20** |
| Knee maximal extension in ST | 0.18* | 0.19** | 0.20** | – | −0.18** | – | – | 0.14* |
| Knee timing of maximal flexion in SW | 0.17* | 0.14* | 0.20** | **0.27***** | – | −0.19** | – | **0.25***** |
| Knee maximal flexion in SW | – | −0.20** | – | – | – | – | – | −0.18* |
| Knee max flexion velocity around TO | **−0.33***** | **−0.46***** | **−0.35***** | – | **0.26***** | – | – | **−0.40***** |
| Ankle max dorsiflexion angle at mid ST | 0.19*** | 0.15* | – | **−0.25***** | – | **0.27***** | – | – |
| Ankle range of motion during push off | −0.14* | **−0.25***** | – | – | – | −0.19** | – | **−0.32***** |
| Ankle maximium dorsiflexion in ST | – | – | – | **−0.44***** | – | **0.51***** | – | – |
| Ankle timing of maximal dorsiflexion in ST | – | – | – | **−0.28***** | – | **0.40***** | −0.19** | – |
| Ankle max plantar flexion velocity around TO | – | **0.26***** | 0.16* | – | – | – | – | **0.29***** |
| Foot mean alignment ST | **0.22**** | 0.15* | – | – | – | – | – | – |
| Ankle second rocker | – | – | – | 0.17* | – | **−0.31***** | 0.17* | – |
| Ankle double bump in ST | – | – | – | – | – | 0.15* | – | – |
| Kinetics | | | | | | | | |
| Hip maximium abduction moment | – | **−0.21*** | – | – | – | **−0.24***** | – | – |
| Hip timing of 0 moment | **0.25***** | **0.27***** | – | – | – | 0.14* | – | **0.30***** |
| Hip maximal power generation in ST | – | – | 0.14* | – | – | **−0.23**** | – | – |
| Hip maximal power absorption in ST | – | – | – | – | – | – | – | – |
| Hip maximal power generation at TO/preSW | – | – | – | −0.15* | – | – | – | – |
| Knee maximal flexion moment in ST | – | – | – | – | – | **0.21**** | – | – |
| Knee maximal extension moment in ST | **0.26***** | **0.24***** | 0.16* | – | **−0.22**** | – | – | **0.32***** |
| Knee maximal power generation in ST | – | – | – | – | – | – | – | – |
| Knee maximal power absorption in ST | −0.15* | −0.19** | – | – | – | **0.22**** | – | −0.16* |
| Ankle peak plantarflexion moment preSW | −0.14* | **−0.21**** | – | −0.17* | −0.18* | – | – | −0.17* |
| Ankle peak power generated at preSW | **−0.28***** | **−0.34***** | **−0.21***** | **−0.28***** | – | – | – | **−0.36***** |
| Ankle peak power absorption at LR | – | – | – | **−0.60***** | – | **0.47***** | **−0.25***** | – |
| EMG data | | | | | | | | |
| Medial hamstrings activity pattern | – | – | – | – | – | – | – | – |
| Lateral hamstrings activity pattern | – | – | – | – | – | – | 0.14* | – |
| Rectus femoris activity pattern in ST | – | – | 0.18** | 0.16* | – | – | – | – |
| Rectus femoris acivity pattern in SW | – | – | – | – | – | – | – | – |
| Tibialis anterior activity at IC | – | – | – | 0.18** | – | −0.16* | – | – |
| Gastrocnemius activity at IC | 0.20** | 0.16* | 0.18* | **0.31***** | – | **−0.27***** | 0.16* | – |
| Vastus lateralis activity pattern | – | – | – | – | – | – | – | – |

AshHipfl: Ashworth score of hip flexors; AshAd90: Ashowrth score of hip adductors (with hip and knee flexed); Ashhamstri: Ashworth score of hamstrings; Ashgastr: Ashworth score of gastrocnemius; Tardhamstr: Tardieu angle of hamstrings; Tardgastr: Tardieu angle of gastrocnemius; Ashtibpost: Ashworth score of tibialis posterior; DunElly: Duncal Ely score; ST: stance; SW: swing; IC: initial contact; TO: toe off; flex: flexion; max: maximal.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

Table 4
Correlation coefficients between gait analysis date and measurements of strength and selectivity, in 200 children with cerebral palsy

| Parameters | StrHip ext | StrHip abd | StrKn Flex | StrKn Ext | StrAnk Dors90 | StrAnk Dors0 | StrPlant Flex | Selhip ext | SelHip Abd | Selkn Flex | Selkn ext | SMCT90 | SMCT0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time and distance | | | | | | | | | | | | | |
| Cadence | – | – | – | – | – | 0.15* | 0.18** | – | – | – | – | – | – |
| Gait velocity | **0.37***** | **0.39***** | **0.30***** | **0.27***** | – | 0.15* | **0.25***** | **0.34***** | **0.36***** | **0.24***** | **0.25***** | – | – |
| Step length | **0.41***** | **0.44***** | **0.22**** | **0.24***** | – | – | 0.16* | **0.39***** | **0.39***** | **0.23***** | **0.27***** | – | – |
| Timing of TO | – | – | – | – | – | – | – | – | – | – | – | 0.15* | – |
| Kinematics | | | | | | | | | | | | | |
| Pelvic mean anterior tilt | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Pelvic range of sagital motion | −0.16* | **−0.28***** | **−0.36***** | **−0.31***** | **−0.31***** | **−0.33**** | **−0.32***** | −0.16* | **−0.26***** | **−0.29***** | **−0.35***** | **−0.30***** | **−0.32***** |
| Pelvic range of coronal motion | – | – | – | – | – | – | 0.16* | – | – | – | – | – | – |
| Pelvic range of transverse motion | – | – | **−0.22**** | – | – | – | – | – | – | – | – | – | – |
| Pelvic mean obliquity angle | – | – | – | – | – | – | – | – | – | – | – | **0.21**** | 0.16* |
| Pelvic mean rotation angle | – | – | – | – | **0.25***** | **0.23**** | **0.21**** | – | – | – | – | **0.35***** | **0.29***** |
| Hip angle at terminal ST | −0.15* | −0.16* | **−0.22**** | **−0.21**** | – | −0.15* | **−0.25***** | – | −0.16* | −0.16* | **−0.21**** | – | −0.14* |
| Hip mean coronal angle in SW | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Hip rotation angle at IC | – | **−0.30***** | −0.18** | −0.16* | – | – | – | – | **−0.28***** | – | – | – | – |
| Hip rotation angle at TO | – | −0.16* | – | – | – | – | – | – | −0.20** | – | – | – | – |
| Hip range of sagital motion in ST | **0.21** | **0.27***** | **0.27***** | **0.29***** | 0.16* | 0.18** | **0.33***** | – | 0.18* | 0.19** | **0.30***** | – | 0.15* |
| Hip maximal flexion in SW | – | – | – | – | – | – | – | – | – | – | – | −0.16* | −0.17* |
| Hip flexion velocity in SW | – | – | – | – | – | – | 0.20** | – | – | – | 0.15* | – | – |
| Knee flexion angle at LR | **0.31***** | **0.24***** | **0.26***** | **0.23**** | **0.24***** | **0.26***** | **0.28***** | **0.28***** | **0.28***** | **0.22**** | 0.19** | **0.27***** | **0.30***** |
| Knee maximal extension in ST | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Knee timing of maximal flexion in SW | – | **−0.24***** | **−0.21**** | −0.19** | **−0.27***** | **−0.24***** | **−0.27***** | −0.19** | **−0.29***** | **−0.25***** | **−0.21**** | **−0.31***** | **−0.27***** |
| Knee maximal flexion in SW | – | **0.26***** | 0.20* | 0.14* | – | – | 0.19** | – | 0.14* | – | **0.23***** | – | – |
| Knee max flexion velocity around TO | 0.15* | **0.28***** | 0.19** | **0.22**** | – | – | **0.24***** | 0.18* | **0.24***** | – | **0.26***** | – | 0.16* |
| Ankle max dorsiflexion angle at mid ST | – | −0.14* | – | – | 0.19** | 0.19** | – | – | – | – | – | 0.16* | – |
| Ankle range of motion during push off | **0.22**** | **0.21**** | **0.23***** | 0.16* | – | – | 0.19** | 0.20** | 0.16* | 0.16* | **0.24***** | – | – |
| Ankle maximium dorsiflexion in ST | – | – | – | – | **0.22**** | **0.21**** | – | – | – | – | – | – | **0.21**** |
| Ankle timing of maximal dorsiflexion in ST | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Ankle max plantar flex velocity around TO | −0.16* | −0.17* | −0.19** | −0.17* | – | −0.16* | **−0.26***** | – | – | −0.15* | −0.17* | – | −0.15* |
| Foot mean alignment ST | – | – | – | 0.15* | 0.16* | 0.18* | 0.18* | – | −0.14* | – | – | 0.20** | 0.19** |
| Ankle second rocker | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Ankle double bump in ST | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Kinetics | | | | | | | | | | | | | |
| Hip maximium abduction moment | – | 0.18** | **0.21**** | – | – | – | – | 0.16* | 0.17* | – | – | – | – |
| Hip timing of 0 moment | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Hip maximal power generation in ST | 0.17* | – | – | – | – | – | – | – | – | – | – | – | – |
| Hip maximal power absorption in ST | – | – | – | −0.16* | – | −0.15* | −0.15* | – | – | – | – | – | – |
| Hip max power generation at TO/preSW | – | **0.24***** | – | – | – | 0.16* | 0.17* | 0.15* | – | – | – | – | – |
| Knee maximal flexion moment in ST | −0.18** | – | – | – | – | – | – | – | – | – | – | – | – |
| Knee maximal extension moment in ST | – | −0.15* | – | – | – | – | – | – | **−0.21**** | – | −0.19** | – | – |
| Knee maximal power generation in ST | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Knee maximal power absorption in ST | – | – | 0.16* | – | – | – | – | – | – | – | – | – | – |
| Ankle peak plantarflex moment preSW | **0.35***** | **0.34***** | 0.16* | **0.22**** | 0.18* | **0.21**** | **0.21**** | **0.36***** | **0.35***** | – | **0.24***** | 0.16* | 0.19** |
| Ankle peak power generated at preSW | **0.37***** | **0.41***** | **0.36***** | **0.36***** | **0.39***** | **0.45***** | **0.48***** | **0.36***** | **0.37***** | **0.27***** | **0.37***** | **0.37***** | **0.41***** |

Table 4 (*Continued*)

| Parameters | StrHip ext | StrHip abd | StrKn Flex | StrKn Ext | StrAnk Dors90 | StrAnk Dors0 | StrPlant Flex | Selhip ext | SelHip Abd | Selkn Flex | Selkn ext | SMCT90 | SMCT0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ankle peak power absorption at LR | – | – | – | – | **0.25**$^{***}$ | **0.22**$^{**}$ | – | – | – | – | – | **0.24**$^{***}$ | 0.20$^{**}$ |
| EMG data | | | | | | | | | | | | | |
| Medial hamstrings activity pattern | – | −0.14$^{*}$ | −0.15$^{*}$ | – | **−0.21**$^{**}$ | −0.19$^{**}$ | −0.19$^{**}$ | – | – | −0.18$^{**}$ | – | −0.18$^{**}$ | −0.18$^{*}$ |
| Lateral hamstrings activity pattern | −0.18$^{*}$ | −0.18$^{**}$ | **−0.21**$^{**}$ | – | – | – | – | – | – | **−0.26**$^{***}$ | – | – | – |
| Rectusfemoris activity pattern in ST | −0.20$^{**}$ | **−0.24**$^{***}$ | **−0.25**$^{***}$ | **−0.36**$^{***}$ | −0.17$^{*}$ | −0.17$^{*}$ | −0.16$^{*}$ | −0.20$^{**}$ | −0.20$^{**}$ | **−0.23**$^{***}$ | **−0.26**$^{***}$ | −0.20$^{**}$ | **−0.21**$^{**}$ |
| Rectusfemoris acivity pattern in SW | **−0.27**$^{***}$ | **−0.26**$^{***}$ | −0.17$^{*}$ | – | – | – | – | −0.20$^{**}$ | −0.19$^{**}$ | −0.16$^{*}$ | – | – | – |
| Tibialis anterior activity at IC | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Gastrocnemius activity at IC | – | **−0.22**$^{**}$ | **−0.21**$^{**}$ | **−0.23**$^{**}$ | **−0.21**$^{**}$ | **−0.22**$^{**}$ | −0.18$^{**}$ | – | −0.16$^{*}$ | – | – | **−0.26**$^{***}$ | **−0.26**$^{***}$ |
| Vastus lateralis activity pattern | **−0.23**$^{***}$ | – | – | – | – | – | – | **−0.21**$^{**}$ | −0.15$^{*}$ | – | – | −0.16$^{*}$ | −0.17$^{*}$ |

StrHipext: strength of hip extensors; StrHipAbd: strength of hip abductors; StrKnFlex: strength of knee flexors; STRKnExt: strength of knee extensors; StrAnkDors90: strength of ankle dorsiflexors (with knee flexed); StrAnkDors0: strength of ankle dorsiflexors (with knee extended); StrPlantFlex: strength of plantar flexors; Selhipext: selectivity of hip extensors; SelHipAbd: selectivity of hip abductors; SelKnFlex: selectivity of knee flexors; Selknext: selctivity of knee extensors; SMCT90: selective motor control test with knee flexed; SMCTO: selective motor control test with knee extended; ST: stance; SW: swing; IC: initial contact; TO: toe off; flex: flexion; max: maximal.

$^{*}$ $p < 0.05$.
$^{**}$ $p < 0.01$.
$^{***}$ $p < 0.001$.

and tibio-femoral angle. The femoral anteversion was measured by palpation of the point of maximal trochanteric prominence as described by Gage [7] and Ruwe et al. [20]. The tibio-femoral angle was measured according to Bleck [2] and Gage [7]. The Modified Ashworth Scale [9], the Modified Tardieu Scale [10], and the Duncan Ely test [2,7] were used to grade spasticity in the hip flexors and adductors, hamstrings, rectus femoris, gastrocnemius and tibialis posterior. Strength in the muscles was evaluated using manual muscle testing. Muscle strength was assessed in the hip extensors and abductors, knee flexors and extensors, ankle dorsiflexors (with knee flexed and extended) and plantar flexors. The scoring of strength in each muscle group was performed on a 10-point ordinal scale as described by Daniels and Worthingham [19]. Selectivity is the ability to move an individual joint independently from the other joints in the same limb and to use only the correct muscle groups during movement [7,10]. Selectivity was assessed in the hip extensors and abductors, knee extensors and flexors, and was scored using a five-point scale, proposed by Trost [21]. Selective motor control of the individual ankle dorsiflexors (with knee flexed and extended) was graded using a method based on Boyd and Graham [10].

### 2.3. Statistical analysis

The association between clinically measured variables and gait parameters was explored by calculating correlation coefficients. The Pearson product-moment correlation coefficient ($r$) was calculated for variables on the ratio scale and Spearman rank correlation coefficient ($r_s$) was used for variables on the ordinal scale. Coefficients with a $p$-value $\leq 0.05$ were considered as significant. The correlations were interpreted according to the guidelines adopted from Altman [22], where $r < 0.20$, poor; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, good; 0.81–1.00, very good.

A series of multiple regression analyses was subsequently carried out in order to establish which combination of clinically measured variables best predicts gait analysis parameters. The gait analysis data were entered as the dependent variables and the clinical measurements were used as the independent variables. The multiple regression analyses were produced by a backward elimination procedure with a significance level of 0.05 as the criterion for an independent variable to be included in the model. The coefficient of determination $R^2$ was calculated for the regression equations. $R^2$ represents the percentage of variance explained by the independent variables to predict a dependent variable. Two models were assessed in the multiple regression analysis. The first model (static model) evaluated the predictive value of 7 ROM and alignment measurements (hip extension, hip abduction evaluated with hip and knee flexed, hip external rotation, bilateral popliteal angle, ankle dorsiflexion evaluated with knee at 0°, femoral

Table 5
Results of the multiple regression analyses to predict gait data based on a static and combined model of clinical measurements ($N = 200$)

| Parameters | Static model | | Combined model | |
|---|---|---|---|---|
| | $R^2$ (%) | Included independent parameters | $R^2$ (%) | Included independent parameters |
| Time and distance | | | | |
| Cadence | 4.6 | **PopABi** | 2.6 | **HipAbd90** |
| Gait velocity | 12.5 | **Adors90**, Hipabd90, hipext | 23.1 | **StrHipAbd**, AshAd90, Tardgastr |
| Step length | 12.0 | **Hipext**, PopABi, **Adors0** | 21.7 | **StrHipAbd**, AshAd90, Tardhamstr |
| Timing of TO | 20.2 | **Adors0**, Hipabd90, Femant, Hipext | 24.2 | **Tardgastr**, StrPlantFI, Hipext, AshAd90, FemAnt, StrAnkdors0 |
| Kinematics | | | | |
| Pelvic mean anterior tilt | 6.9 | **PopABi**, Hipabd90, Adors0 | 19.4 | **DunElly**, Tardhamstr, Tardgastr |
| Pelvic range of sagital motion | 0.0 | – | 20.1 | **StrAnkDors0**, Tardhamstr, DunElly, AshAd90 |
| Pelvic range of coronal motion | 0.0 | | 6.2 | **StrPlantfl**, Tardgastr |
| Pelvic range of transverse motion | 0.0 | – | 2.4 | **AshHipfl** |
| Pelvic mean obliquity angle | 8.8 | **Hipabd90**, Adors0 | 10.9 | **HipAdb90**, Ashad90, AshhipFI |
| Pelvic mean rotation angle | 10.7 | **Hipabd90** | 19.4 | **HipAbd90**, StrPlantfl, AshAd90 |
| Hip angle at terminal ST | 24.7 | **Hipad90**, Hipext, TibFemA | 33.9 | **HipAbd90**, StrPlantfl, DunElly, Hipextrotsup |
| Hip mean coronal angle in SW | 2.1 | **PopABi** | 2.4 | **StrHipAbd** |
| Hip rotation angle at IC | 17.3 | **Femant**, Hipextrotsup, PopABi | 18.3 | **FemAnt**, StrHipAbd, Hipextrotsup |
| Hip rotation angle at TO | 18.8 | **Hipabd90**, Femant | 23.0 | **FemAnt**, Hipabd90, StrAjnkdors0, StrHipAbd |
| Hip range of sagital motion in ST | 19.4 | **Hipabd90**, TibfemA, Hipextrotsup, Adors0, PopABi | 33.9 | **StrPlantfl**, HipAbd90, Tardgastr, Hipextrotsup, Tardhamstr |
| Hip maximal flexion in SW | 3.0 | **Adors0** | 11.7 | **Tardgastr**, DunElly |
| Hip flexion velocity in SW | 21.0 | **Hipabd90**, TibfemA, Femant | 22.2 | **HipAbd90**, StrPlantfl |
| Knee flexion angle at LR | 0.0 | – | 2.5 | **StrHipAbd** |
| Knee maximal extension in ST | 14.9 | **Hipabd90**, TibfemA | 18.1 | **Hipabd90**, StrPlantfl, StrAnkDors0, TibFemA |
| Knee timing of maximal flexion in SW | 2.0 | **PopABi** | 15.6 | **StrHipAbd**, DunElly, Tardgastr |
| Knee maximal flexion in SW | 0.0 | – | 7.9 | **StrPlantfl**, StrHipAbd |
| Knee max flexion velocity around TO | 0.6 | **HipAbd90**, Adors0, Hipext | 1.0 | **Hipabd90**, AshAd90, StrPlantfl |
| Ankle max dorsiflexion angle at mid ST | 10.7 | **Adors0**, Hipabd90 | 12.9 | **Tardgastr**, StrAnkDors0 |
| Ankle range of motion during push off | 9.6 | **Hipabd90**, TibfemA | 17.3 | **Tardgastr**, Hipabd90, Tardgastr |
| Ankle maximium dorsiflexion in ST | 24.8 | **Adors0**, PopABi | 30.0 | **Tardgastr**, Tardhamstr |
| Ankle timing of maximal dorsiflexion in ST | 11.3 | **Adors0**, PopABi | 22.0 | **Tardgastr**, Tardhamstr, AshAd90 |
| Ankle maximal plantar flexion velocity around TO | 11.8 | **Hipabd90**, TibfemA | 18.0 | **HipAbd90**, StrPlantfl, TibFemA |
| Foot mean alignment ST | 32.4 | **TibFemA**, Femant, Hipabd90 | 34.9 | **TibFemA**, AshAd90, FemAnt |
| Ankle second rocker | 6.5 | **Adors0**, PopABi | 16.1 | **Tardgastr**, Ashad90, StrPlantfl, Tardhamstr |
| Ankle double bump in ST | 0.0 | – | 2.4 | **Tardgastr** |
| Kinetics | | | | |
| Hip maximium abduction moment | 8.2 | **Adors0**, Hipext | 12.3 | **Tardgastr**, StrHipAbd, Hipext |
| Hip timing of 0 moment | 10.7 | **Hipabd90**, Femant, TibfemAnt | 14.9 | **FemAnt**, DunElly, AshAd90 |
| Hip maximal power generation in ST | 0.0 | – | 5.2 | **Tardgastr** |
| Hip maximal power absorption in ST | 4.1 | **TibFemA** | 4.1 | **TibFemA** |
| Hip maximal power generation at TO/preSW | 4.9 | **PopABi**, tibFemA | 6.6 | **StrHipAbd**, TibFemA |
| Knee maximal flexion moment in ST | 0.0 | | 8.0 | **StrAnkDors0**, Tardgastr |
| Knee maximal extension moment in ST | 6.1 | **HipAbd90** | 11.7 | **DunElly**, StrAnkDors0 |
| Knee maximal power generation in ST | 0.0 | – | 0.0 | – |
| Knee maximal power absorption in ST | 8.5 | **PopABi**, Hipext, TibFemA, Hipextrotsup | 9.8 | **AshAd90**, Tardgastr |
| Ankle peak plantarflexion moment preSW | 10.1 | **PopABi**, Hipextrotsup | 24.2 | **Tardhamstr**, StrHipAbd, StrPlantfl, Ashad90, Hipextrotsup |
| Ankle peak power generated at preSW | 9.3 | **Hipext**, PopABi | 34.1 | **StrHipAbd**, AshAd90, StrPlantfl, StrAnkDors0, FemAnt |
| Ankle peak power absorption at LR | 18.6 | **Adors0** | 27.6 | **Tardgastr**, StrAnkDors0 |
| EMG data | | | | |
| Medial hamstrings activity pattern | 3.1 | **Hipabd90** | 5.9 | **HipAbd90**, StrHipAbd |
| Lateral hamstrings activity pattern | 0.0 | – | 4.3 | **StrHipAbd**, Hipextrotsup |
| Rectus femoris activity pattern in ST | 2.0 | **Hipext** | 4.5 | **StrHipAbd** |
| Rectus femoris acivity pattern in SW | 0.0 | – | 7.1 | **StrHipAbd**, HipAbd90 |
| Tibialis anterior activity at IC | 0.0 | – | 2.1 | **Tardgastr** |

Table 5 (*Continued*)

| Parameters | Static model | | Combined model | |
|---|---|---|---|---|
| | $R^2$ (%) | Included independent parameters | $R^2$ (%) | Included independent parameters |
| Gastrocnemius activity at IC | 7.3 | **Adors0**, Hipext | 13.0 | **Tardgastr**, StrHipAbd |
| Vastus lateral is activity pattern | 0.0 | – | 0.0 | – |

Hipext: hip extension; Hipabd90: hip abduction (with hip and knee flexed); Hipextrot: hip external rotation; PopAbi: bilateral popliteal angle; Adors0: ankle dorsiflexion with knee extended; FemAnt: femoral anteversion; TibFemA: tibio-femoral angle; AshAd90: Ashowrth score of hip adductors (with hip and knee flexed); Tardhamstr: Tardieu angle of hamstrings; Tardgastr: Tardieu angle of gastrocnemius; DunElly: Duncal Elly score; StrHipAbd: strength of hip abductors; StrAnkDors0: strength of ankle dorsiflexors (with knee extended); StrPlantfl: strength of plantar flexors; ST: stance; SW: swing; IC: initial contact; TO: toe off.

anteversion and tibio-femoral angle). In the second model (combined model) a combination of ROM, alignment, spasticity and strength measurements was evaluated. This model was defined to be more dynamic than the first model. It was hypothesised that a dynamic model would be more closely related to gait data than a static model. Therefore, in this model, the Tardieu angle was selected instead of the passive ROM. If the Tardieu angle was not available, it was replaced by a combination of Ashworth score and ROM measurement. For the hip flexors, the Ashworth score was not included because of the significant inter-correlation ($p < 0.001$) with hip extension ROM. Finally, a set of strength parameters was added. The final model included 12 independent variables (ROM for hip extension and hip abduction, hip external rotation, femoral anteversion, tibio-femoral angle, Ashworth score for hip adductors, Tardieu angle for hamstrings and gastrocnemius, Duncan Ely score and strength of hip abductors and ankle dorsi- and plantar flexors).

All statistical procedures were performed with the SAS system (SAS Institute Inc., SAS Campus Dr., Cary, NC 27513).

## 3. Results

### 3.1. Correlation between clinical measurements and gait data

Tables 2–4 summarise the significant correlation coefficients ($p$-value $< 0.05$) between 49 gait analysis parameters and 32 clinical measurements. None of the correlations were good or very good. The correlations printed in bold in Tables 2–4 were fair (0.21–0.40) to moderate (0.41–0.60).

Results for *ROM and alignment measurements with gait data* are presented in Table 2. In general, values of Pearson correlation coefficients ($r$) for ROM and alignment were low. Of all correlation coefficients, 13% were fair to moderate, with the overall highest correlation being 0.50. Time and distance parameters and EMG data only showed low or fair correlations to ROM and alignment measurements. Clinical measurements of ROM at the hip joint in the sagittal and coronal plane showed the highest percentage of fair to moderate associations with gait analysis parameters.

Significant Pearson ($r$) and Spearman ($r_s$) correlation coefficients between *gait analysis parameters and measurements of spasticity* are presented in Table 3. Spasticity measurements also revealed a low relationship between most data compared. 19.4% of the correlations were fair to moderate. Spasticity measurements of hip adductors and M. rectus femoris showed the highest percentage of fair to moderate relations with gait analysis parameters. However, the highest correlation was shown between the Ashworth score of the M. gastrocnemius and ankle peak power absorption at loading response ($r_s = -0.60$).

Further relationship was explored using the Spearman rank correlation coefficients ($r_s$) *for clinical measurements of strength and selectivity and gait analysis data* (see Table 4). Although the results revealed a high number of significant correlations, the values were again predominantly low. A high number of significant correlations were found for strength and selectivity measurements to time and distance parameters, and to EMG data (respectively, 42.3% and 49.4% of the correlations). In total, 23% of the correlation coefficients for strength measurements and 17.7% for selectivity measurements were fair to moderate. The highest correlation was found for strength in ankle plantar flexors and dorsiflexors to ankle peak power generated at preswing ($r_s = 0.48$ and 0.45, respectively).

### 3.2. Multiple regression analysis

The results of the multiple regression analyses, including the $R^2$-values and the selected clinical parameters in the regression equation for both the static and the combined model, are summarised in Table 5. The independent parameter with the highest unique contribution to the total $R^2$ is printed in bold.

All $R^2$-values obtained by the multiple regressions were $<35\%$ and about half of the $R^2$-values were $<10\%$. The variance of all gait variables was better explained by the combined model compared to the static model, except for three variables (cadence, knee maximum power generation in stance, hip power absorption in stance). The $R^2$ of these three variables was very low for both models ($R^2 < 5\%$). This is illustrated in Fig. 1, which represents the $R^2$-values for the static and combined model, for the time and distance parameters, the kinematic and kinetic data of ankle, knee, hip and pelvis and the EMG variables.

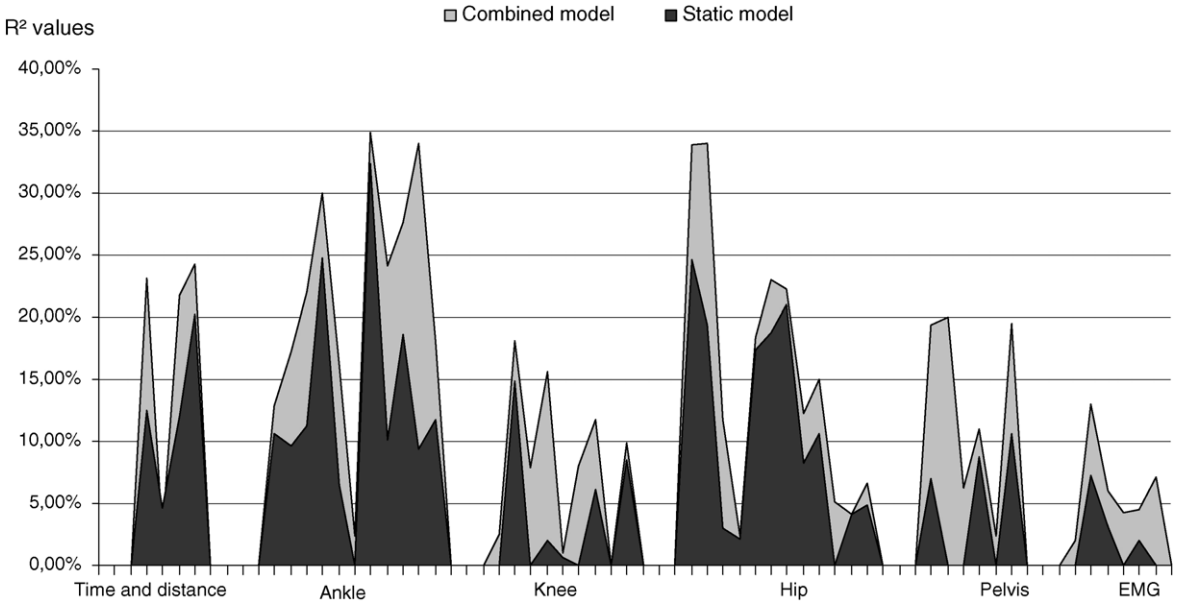


Fig. 1. $R^2$-values of multiple regression analysis based on the static and combined model for four time and distance parameters, kinematics and kinetics of ankle (11 parameters), knee (9 parameters), hip (12 parameters), pelvis (6 parameters) and 7 EMG variables.

## 4. Discussion

Although significant correlations were detected for various clinical measurements to gait data, in general the *r*-values were low. This was in consistency with Orendurff et al. [14] and McMulkin et al. [6], who also reported poor correlations between clinical examination measurements and dynamic motion. However, these two studies only included ROM parameters. Our study was elaborated by including also spasticity, strength and selectivity measurements. However, we were not capable to demonstrate high correlations.

General comparison of all correlation tables revealed that clinical measurements of strength and selectivity had the highest degree of significant correlation with gait analysis data compared to the ROM and spasticity measurements. Fair to moderate correlations to gait data were most frequently found for strength measurements (23% of the correlations), compared to selectivity (17.7%), spasticity (19.4%) and ROM measures (13%). In this respect, our findings support our hypothesis that, due to the dynamic character of gait, clinical measurements of spasticity, strength and selectivity would show a higher relationship with gait data than static ROM measurements.

It is interesting to note that all clinical measurements for the hip in the coronal plane (ROM for hip abduction, spasticity of hip adductors and strength of hip abductors) showed the highest number of fair to moderate correlations to gait data. We found consistency between the results for ROM, spasticity and strength and selectivity, as the above-mentioned clinical hip measurements in general correlated to the same gait variables (most significantly to maximal hip extension and hip rotation at terminal stance and to hip and knee angular velocity at initial swing). Surprisingly, the above-mentioned hip measurements in the coronal plane also correlated with ankle kinetics ($r = 0.41$ between strength of hip abductors and the ankle peak power generation at preswing). We expected that the ankle kinetics would mainly correlate to strength measurements of plantar flexors. Indeed, the correlation was moderate ($r = 0.48$ between strength of gastrocnemius and the ankle power generation at preswing). The underlying explanation for the similarity between these two moderate correlations might be the coordinated flow of muscle activity during walking from proximal to the distal segments of the lower limb [18] and the impact of distal instability on the proximal joints.

We expected high correlation of hip rotations in gait with femoral anteversion, as reported by Gage et al. [23]. This correlation was only fair for hip rotation at initial contact and at toe off (respectively, 0.28 and 0.29). Orendurff et al. [14] and Aktas et al. [15] also reported a low correlation between femoral anteversion and hip rotation. Hip rotation at the end of stance phase was fairly correlated with spasticity of hip flexors ($r_s = 0.30$) and with contractures of hip adductors ($r = -0.38$). Both muscles are known as internal rotators of the hip [7,24].

We found that time and distance parameters mainly correlated with strength and selectivity measurements. Damiano et al. [13,25] also found moderate to good correlations between strength in the lower limb muscles and velocity and cadence in 11 children with CP. Their correlations were higher than the values reported in this study. However, the method for evaluating muscle strength was different. The hand-held dynamometer was used to assess strength, while the manual muscle testing technique was used in our study.

Our study results revealed that the majority of spasticity measurements have a low relationship to gait data. Damiano and Abel [26] reported that Ashworth scores were weakly correlated with functional measurements.

Skold et al. [27] found moderate to high correlations of spasticity measurements to EMG recordings in gait in 38 tetraplegic patients ($r$-values between 0.56 and 0.95). In our study, mainly strength and selectivity measurements significantly correlated to EMG data, but only at a fair level. In addition to spasticity measurements of hip adductors, rectus femoris spasticity measurements also showed a high percentage of fair to moderate relations with gait analysis parameters. Damiano et al. [28] also reported a significant correlation coefficient between the knee extensor Ashworth score and the walk, run and jump score of the GMFM test ($r = -0.57$). Spasticity of the rectus femoris has been cited as the primary cause of stiff knee gait [7–18]. Duncan Ely score showed indeed inverse correlation to knee flexion velocity at initial swing ($r_s = -0.40$) and also to hip flexion velocity ($r_s = -0.34$) and ankle power generation at preswing ($r_s = -0.36$). Knee flexion velocity was also significantly correlated to hip extension and abduction ROM ($r = 0.40$ and 0.50, respectively), and to a large number of strength and selectivity measurements. These findings are in agreement with Kerrigan et al. [29,30] who reported alternative causes of stiff knee gait including impaired dynamic hip flexion and poor ankle mechanics.

This study was performed on a large group of patients ($N = 200$). The gait analysis parameters were defined by one kinesiologist, who was blind to the results of the clinical examination. The clinical measurements were performed by three well-trained kinesiologists, who frequently have special training and discussion sessions to ensure the standardisation of the measurements. It should be noted that, apart from the diagnosis, our patient group was homogeneous, characterized by a relative high functional level and a limited age range. This might have influenced the study results. It is likely that severe bony deformities, high level of spasticity, severe weakness and lack of selectivity more clearly impair gait. Correlation procedures are sensitive to the range of values [28]. By including more severely involved and older children with CP, the relationship between clinical measurements and gait data might be improved. Damiano et al. [28] suggested that sampling differences across studies may explain many of the differences reported in the literature. It would therefore be interesting to focus future research also on subgroups (hemiplegia, diplegia) and to study the impact of previous surgery on the relation between gait data and clinical measurements.

Multiple regression analysis revealed that adding dynamic clinical measurements (spasticity, strength and selectivity) to a static model (ROM) improved the relationship between clinical measurements and gait data. In the multiple regression analysis, dynamic parameters (like Ashworth and Tardieu scores and strength and selectivity measures) were frequently selected for the dynamic model, except for the parameters indicating rotational gait deviations (foot alignment and hip rotation). For rotational gait deviations, there was marked similarity between the retained parameters in both models. Clinical measurements of spasticity of gastrocnemius and strength of hip abductors were frequently included in the multivariate analysis, and this was the case for a variety of gait analysis parameters at all joint levels (ankle, knee, hip and pelvis). A frequently selected static clinical measurement for many gait parameters at all levels was ROM for hip abduction.

In general, the variance of the gait data was better explained by a combined model of static and dynamic clinical measurements, compared to a purely static model. However, our results also indicate that gait analysis parameters cannot be accurately predicted by a combination of clinical measurements. $R^2$-values were low, suggesting that other factors play a role in dynamic motion than contractures, spasticity, strength and selectivity of different muscle groups. Several factors may explain the low correlation and $R^2$-values found in this study. In the clinical assessment all muscles are evaluated in a mono-articular way. However, bi-articular muscles behave differently during gait. We clinically evaluate isolated muscle groups at each joint level, but pathological gait is defined by interactions of multiple limitations, co-contractions and muscle synergies. The clinical examination focuses on primary and secondary problems, while pathological gait is characterized by compensation mechanisms (tertiary problems) [3,11] to overcome the primary and secondary problems. Another differentiating factor is that in gait analysis, motions are defined by mathematical joint models based on marker placement, which is a simplification of the real anatomical situation evaluated in the clinical examination. Finally, in the clinical examination, simple motions are evaluated at standardized velocity. In contrast, gait is complex, characterized by total patterns, intra-limb and inter-limb coordination, balance problems and interactions across planes and levels. The lack of a high relationship between clinical examination and gait data does not indicate that one measurement is superior to the other in clinical decision-making. The independence of the measurements supports the notion that both data sets are critical considerations. We can conclude that multiple parameters, including subsets of clinical examination and gait analysis data, considered together may prove to be the best method of delineating the problems of children with CP.

## References

[1] Olsson E, Barck A. Correlation between clinical examination and quantitative gait analysis in patient operated upon with the gunston-hult knee prosthesis. Scand J Rehab Med 1986;18:101–6.

[2] Bleck EB. Orthopaedic management in cerebral palsy. London: Mac Keith Press, 1987. p. 49–64.

[3] Gage JR. The role of gait analysis in the treatment of cerebral palsy. J Pediatr Orthop 1994;14:701–2.
[4] Damiano DL, Vaughan CL, Abel MF. Muscle response to heavy resistance exercise in children with spastic cerebral palsy. Dev Med Child Neurol 1995;37:731–9.
[5] Somers DL, Hanson JA, Kedzierski CM, Nestor KL, Quinlivan KY. The influence of experience on the reliability of goniometric and visual measurement of forefoot position. JOSPT 1997;25:192–202.
[6] McMulkin ML, Gulliford JJ, Williamson RV, Major MC, Ferguson RL. Correlation of static to dynamic measures of lower extremity range of motion in cerebral palsy and control populations. J Pediatr Orthop 2000;20:366–9.
[7] Gage JR. The treatment of gait problems in cerebral palsy. London: Mac Keith Press, 2004.
[8] Ashworth B. Preliminary trial of carisoprodol in multiple sclerosis. Practitioner 1964;192:540–2.
[9] Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of spasticity. Phys Ther 1987;67:206–7.
[10] Boyd RN, Graham HK. Objective measurement of clinical findings in the use of botulinum toxin type A for the management of children with cerebral palsy. Eur J Neurol 1999;8(Suppl 6):S23–35.
[11] DeLuca PA, Davis RB, Ounpuu S, Rose S, Sirkin R. Alterations in surgical decision making in patients with cerebral palsy based on three-dimensional gait analysis. J Pediatr Orthop 1997;17:608–14.
[12] Damiano DL, Abel MF. Relation of gait analysis to gross motor function in cerebral palsy. Dev Med Child Neurol 1996;38:389–96.
[13] Damiano DL, Abel MF. Functional outcomes of strength training in spastic cerebral palsy. Arch Phys Med Rehab 1998;79:119–25.
[14] Orendurff MS, Chung JS, Pierce RA. Limits to passive range of joint motion and the effect on crouch gait in children with cerebral palsy. Gait Posture 1998;7:165–6.
[15] Aktas S, Aiona MD, Orendurff M. Evaluation of rotational abnormalities in the patients cerebral palsy. J Pediatr Orthop 2000;20:217–20.
[16] Inman VT, Ralston HJ, Todd F. Human walking. Baltimore: Williams & Wilkins, 1991.
[17] Winter DA. The biomechanics and motor control of human walking. Waterloo: University of Waterloo Press, 1987.
[18] Perry J. Gait analysis: normal and pathological function. Thorofare: SLACK Inc., 1992.
[19] Daniels L, Worthingham C. Muscle testing techniques of manual examination. Philadelphia: WB Saunders, 1986. p. 4–26.
[20] Ruwe PAs, Gage JR, Ozonoff MB, DeLuca PA. Clinical determination of femoral anteversion. J Bone Joint Surg 1992;74:820–30.
[21] Trost J. Physical assessment and observational gait analysis. In: GageJ.R., editor. The treatment of gait problems in cerebral palsy.. London: Mac Keith Press; 2004. p. 71–89.
[22] Altman DG. Practical statistics for medical research. London: Chapman & Hall, 1991. p. 404.
[23] Gage JR, DeLuca PA, Renshaw TS. Gait analysis: principles and applications. J Bone Joint Surg 1995;77-A:1607–23.
[24] Delp SL, Arnold AS, Speers RA, Moore CA. Hamstrings and psoas lengths during normal and crouch gait: implications for muscle-tendon surgery. J Orthop Res 1996;14:144–51.
[25] Damiano DL, Dodd K, Taylor NF. Should we be testing and training muscle strength in cerebral palsy? Dev Med Child Neurol 2002;44:68–72.
[26] Damiano DL, Abel MF. Relationships among impairments, motor function, and perceived health status in spastic cerebral palsy: a multicenter collabration. Dev Med Child Neurol 2000;42(Suppl 83):42.
[27] Skold S, Harms-Ringdahl K, Hultling C, Levi R, Seiger A. Simultaneous Ashworth measurements and electromygraphic recording in tetraplegic patients. Arch Phys Med Rehab 1998;79:959–65.
[28] Damiano DL, Quinlivan JM, Owen BF, Payne P, Nelson KC, Abel MF. What does the Ashworth scale really measure and are instrumented measures more valid and precise? Dev Med Child Neurol 2002; 44:112–8.
[29] Kerrigan DC, Burke DT, Nieto TJ, Riley PO. Can toe-walking contribute to stiff-legged gait? Am J Phys Med Rehab 2001;80:33–7.
[30] Kerrigan DC, Karvosky ME, Riley PO. Spastic paretic stiff-legged gait: joint kinetics. Am J Phys Med Rehab 2001;80:244–9.