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Determinants of Gait as Applied to Children with Cerebral Palsy

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Introduction

During walking the body center of mass (CoM) moves up and down, reaching a maximum during single limb support and a minimum during double limb support. The work required for this vertical movement of the CoM is approximately 50% of the total work for walking[1,2]. For persons with neuromuscular disorders such as stroke or cerebral palsy, the CoM vertical excursion may be increased. To date little work has been done to quantify the contributions of the body kinematics resulting in the increased CoM excursion experienced by children with CP. Understanding the kinematic conditions resulting in CoM vertical excursion may provide insights for specific treatments.

Saunders, Inman, and Eberhart[3] in their classic paper on human walking sought to identify kinematic characteristics or “gait determinants” that impact on the excursion of the body CoM. They empirically identified three determinants; pelvic rotation, pelvic obliquity, and single support knee flexion which would minimize the vertical displacement of the CoM. Saunders et al. proposed that pelvic rotation would raise the CoM at its low point in double limb support while pelvic obliquity and knee flexion would lower the high point of CoM excursion during single limb stance. The coordinated action of the knee and ankle were described as being important to smoothing the CoM transition between its high and low points resulting in a low amplitude sinusoidal CoM motion.

Recent quantitative research has modified our understanding of the relative contributions of gait determinants on CoM vertical motion. Gard and Childress[4–6] found that pelvic obliquity and single support knee flexion did not significantly reduce the CoM excursion in walking at comfortable speeds. Other studies estimated that pelvic rotation accounts for only a 10% reduction in CoM excursion[7,8]. Della Croce, et al.[7] defined five new determinants: ipsi-, contra-lateral knee flexion, and heel rise in double limb support at CoM minimum and leg inclination, and heel rise at CoM maximum in single limb support, to more completely explain the CoM vertical excursion. Ipsi-, contra-lateral knee flexion, in double support, and heel rise, in single support, differ from the other determinants in that their action increases rather than decreases the excursion of the CoM. Of these new determinants they found that heel rise during

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double limb support had the greatest impact and resulted in approximately a 66% reduction of CoM excursion.

The roles of the above 8 determinants on vertical excursion have never been examined or quantified for children or children with cerebral palsy (CP). The large metabolic cost of walking experienced by children with CP draws interest to the vertical excursion of their CoM. Children with CP walk with a gait which characteristically uses two to three times as much energy as typically developing children [9], while walking at a slower self selected comfortable pace [10]. Our studies have demonstrated that the potential/kinetic energy exchange, a major energy saving mechanism of gait, is less efficient in children with CP[11]. This poor energy exchange is in part created by a larger CoM vertical excursion, and thus potential energy variation, than is seen in typically developing children. Cavagna et al.[12] have shown that potential energy is a reliable predictor of total biomechanical energy. Kerrigan et al.[13] also demonstrated that the vertical excursion of the CoM reliably predicts the oxygen consumption during walking. By examining the effect of determinants on CoM, we hope to gain insight into the high metabolic cost of gait in children with CP.

In the present study we used the methodology of Della Croce, et al.[7] to quantify the isolated contributions of the 8 determinants of gait on the vertical CoM displacement of both typically developing children and children with CP. Such a comparison provides insight into the walking patterns of children with CP and their increased energy required for ambulation. We hypothesized that CoM vertical excursion would be increased in CP but that the relative contributions of the determinants to vertical CoM excursion of children with CP would be the same as the age-matched controls because the children with CP employ a similar reciprocating walking strategy.

Methods

Subjects and Procedures

The kinematic data of 23 children were collected and analyzed. This group of children consisted of two populations. The first group of age-matched controls was comprised of 13 children without known musculoskeletal, neurological, cardiac, or pulmonary pathology, and included 6 females and 7 males averaging 12.4 ± 2.8 years of age, 149.0 ± 17.3 cm in height, and 46.1 ± 17.0 kg in mass. The second group consisted of 10 children diagnosed with spastic diplegic CP. These subjects were community ambulators who did not use walking aids. They included 2 females and 8 males averaging 10.0 ± 3.6 years of age, 139.5 ± 22.0 cm in height, and 36.3 ± 14.1 kg in mass. All tests were conducted in the Motion Analysis and Motor Performance Laboratory at the University of Virginia. Subject assent and parental consent was approved by the University of Virginia's Human Investigation Committee and was obtained for all subjects.

A full body marker set of 38 markers was attached to all 10 of the Cerebral Palsy subjects and 6 of the controls. The other 7 controls were part of a database collected before the 38 marker set was adopted and used reduced marker sets consisting of pelvis and lower extremity markers. Subjects were instructed to walk barefoot along the 10m laboratory walkway at their self selected comfortable walking speed. Three-dimensional kinematic data were collected using a six camera Vicon Motion Analysis System (Oxford Metrics, UK) at 120 Hz. Each subject completed a minimum of 5 trials assuring there would be sufficient trials with clean continuous walking. The measurement volume of the Vicon system allowed for the capture of two to five steps per trial. The determinant analysis was applied to each step and the values averaged.

For each subject, the length of the shank and thigh segments and the geometry of the pelvis were estimated during a static standing trial. Shank length was defined as the distance between ankle joint center and knee joint center, thigh length was defined as the distance between the

knee joint center and the hip joint center, pelvis width was defined as the distance between the hip joint centers. The CoM vertical position during walking was estimated differently with respect to the marker set used. For subjects with full body marker sets the CoM was calculated using the full body multi-segment kinematics model[14]. The CoM for subjects whose data was collected using only the lower body marker set was estimated using the sacral marker. Previous studies have demonstrated the pattern of vertical displacement for these two methods are nearly identical [13,15,16]. We found no difference between the excursions of the sacral marker and the computed CoM for the controls with full body marker sets ($p>0.60$) or between the excursion of the sacral marker of the controls with lower body marker set and that of the CoM in the full body marker set ($p>0.20$).

Data Analysis

The determinants of gait were computed using the methodology of Della Croce et al.[7]. This method computes the effects of the determinants using one model during double support and a simpler model during single support. The modified compass gait model (Model 1) shown in Figure 1 was applied at the instant of time of minimum CoM height (during double support). This model included the definition of thighs and shanks instead of a rigid lower limb and a segment representing the pelvis. Three additional cylindrical joints describing ipsi- and contra-lateral knee flexion and pelvic rotation facilitated motion of these segments. A linear joint was also added to represent heel rise. For each trial the model geometry was defined using the 3-D position of each joint center determined from a subject's kinematics at the instant of minimum CoM. The isolated contributions of an individual determinant were computed as the difference between the CoM minimum height and the corresponding minimum calculated using the model with the individual determinant set to zero. This data was normalized by the clinically measured excursion of each subject to account for leg and step length differences.

The second model (Model 2, Figure 2), composed of three segments representing thigh, shank, and pelvis, was used to evaluate the effects of determinants at the maximum CoM height (during single support). The effects of single support knee flexion, leg inclination (i.e. the antero-posterior distance between hip and ankle joint centers of the supporting limb), pelvic obliquity, and single support heel rise on the maximum CoM height were computed in the same manner as used for Model 1.

For the purpose of normalization, a third simple compass gait model, was used to compute the excursion a subject would have for his or her average step and leg length if they had neither ankle or knee joints. As vertical excursion has been shown to be a function of both step and leg length[7], this value was used to normalize the measured excursion. The simple compass gait excursion was also used in the model validation analysis.

In an effort to quantify the accuracy of our models a prediction ratio (PR) was calculated. The total predicted excursion $Z_{\text{predicted}}$ can be determined as the difference between the maximum possible excursion for a subject, predicted by the simple compass gait model Z_{compass} , and the sum of the effects of the determinants Z_{det} :

$$Z_{\text{predicted}} = Z_{\text{compass}} - \sum Z_{\text{det}}$$

This leads to the prediction ratio, the ratio between the predicted excursions $Z_{\text{predicted}}$, and the actual measured excursion Z_{total} .

$$PR = \frac{Z_{predicted}}{Z_{total}}$$

In this format a model predicting the actual clinically measured excursion would have a prediction ratio of one.

Between group comparisons of the dependent measures were made with 1-way analysis of variance using the software program Statistica 5.1. Validation of the assumption of normal distribution was confirmed through subsequent nonparametric analysis.

Results

All subjects were able to walk through the test volume several times without assistance. Typical of previous research, when asked to walk at their self selected comfortable walking speed the control group walked with a longer normalized step length (84% leg length, controls, 71% leg length, CP, $P < 0.001$). Despite walking with longer step lengths, the controls also experienced less (52% compass gait, controls, 86% compass gait, CP, $P < 0.001$) vertical excursion when normalized by the predicted simple compass gait excursion. The models predicted the total excursion for both groups accurately the models resulted in a prediction ratio of 1.08 for the controls and 1.19 for the data collected on children with CP. We found no correlations between the effects of the determinants and the age, sex, weight, or height of subjects.

The relative contribution of the determinants, both positive (beneficial) and negative (detrimental), towards the total vertical CoM displacement are shown in Figure 3. Note that the direction of change was similar for controls and for patients with CP. At CoM minimum position in double support, ipsi- and contra-lateral knee flexion increased CoM excursion, while pelvic rotation and heel rise reduced excursion for both groups. However, the detrimental effects of ipsi-lateral knee flexion were more pronounced for the CP subjects where its effects were 55% of the measured excursion compared to a 24% increase for controls ($P < 0.005$). Contra-lateral knee flexion also had a larger effect in the children with CP increasing the CoM excursion by 46% for the subjects with CP vs. 18% for the controls ($P < 0.001$). Pelvic rotation resulted in a greater reduction of excursion, increased the minimum height for the children with CP by 29% of the total excursion and 42% for the controls ($P < 0.014$). Heel rise both resulted in a raising the CoM at the instant of minimum CoM excursion, with no significant between group differences but does represent the largest reduction of CoM excursion 87% and 84% of total excursion respectively for the subjects with CP and controls.

Maximum height of the CoM during single limb support was less influenced by the identified determinants. Single support knee flexion and leg inclination lowered the maximum height, while pelvic obliquity, with standard deviations greater than the reported values, had no effect. Heel rise in single support had the more detrimental effect in the group with CP (29% vs only 4.7% in the controls, ($P < 0.008$)) by raising CoM excursion. Single support knee flexion reduced CoM excursion (beneficial) 30% in the children with CP and 18% in the controls, but the difference was not significant. Leg inclination reduced CoM excursion more in the children with CP, 37%, ($P < 0.011$) than in the controls, 17%.

Discussion

Our findings on the effect of the determinants of gait in the controls are consistent with previously published research. The results of Della Croce et al.[7] are within a standard deviation of the results for the controls in this study with two exceptions; the effects of pelvic rotation and leg inclination. The effect of pelvic rotation on CoM excursion in the controls was

twice as large as that found in adults by Della Croce et al.[7], while the effects of leg inclination were slightly smaller in the present study. The controls walked with longer normalized step lengths (.84 leg length) than the published data on adults (.69 leg length). The larger pelvic rotation of the controls is likely a result of the longer normalized step lengths. Overall these results confirm that children of these ages walk with a mature gait.

When applied to the gait of subjects with CP the determinant analysis found effects that were similar to those found in the controls for the determinants which reduced CoM excursion, but the effects of determinants which resulted in increases in CoM excursion were significantly greater in the children with CP. Knee flexion of both legs during double support coupled with excessive heel rise in single limb support more than twice the effect on the CoM excursion in the children with CP as these parameters did with the controls. The only determinant that had a positive effect and was greater in the children with CP was leg inclination though this was offset by pelvic rotation that resulted in a greater reduction for the controls.

Thus the children with CP were able to exploit the kinematic determinants that reduce CoM excursion in a manner quite similar to the controls. However, they were unable to reduce the negative determinants to the same degree as the controls. The reasons for these deficits are obviously multifaceted in children with CP. The increased knee flexion in double support may be to accommodate the extended ankle position at foot contact or result from tight hamstring muscles or both. The increased heel rise in single support may reflect a spastic response in tight triceps surae muscles. In addition, it may also reflect a solution to clearing the swing foot with the foot plantarflexed rather than dorsiflexed. Naturally other factors such as muscle weakness and poor motor control could have an impact on these determinants.

The reduced effectiveness of pelvic rotation in the group with CP can be attributed to the shorter steps length they employ in ambulation, as increased pelvic rotation is a strategy used to increase step length. The increased effect of leg inclination, which reduced CoM excursion, is unlikely to have an overall positive effect on the gait of children with CP. The results of this study are in line with previous research[11] that show the peak in CoM height is delayed in children with CP. While this results in a reduced CoM excursion it also reflects the fact that the peak in potential energy occurs too late to allow optimal energy transfer between the potential and kinetic energies. This transfer is a major mechanism for energy conservation during walking. Previous work has shown that energy recovery in children with CP is only two-thirds of that in typically developing children[11] thus negating the positive effect of the reduced excursion. This point highlights the fact that the determinants of gait analysis does not provide insight into the poor motor timing or lack of propulsion in gait which are present in children with CP.

Della Croce et al.[7] found a deviation of approximately 8% between the modeled and actual excursions. This is similar to the 7.6% deviation we found in the controls. However, the measured excursions of the patients with CP deviated 19% from the model. The application of the methodology of Della Croce et al.[7] assumes that the deviation of the CoM vertical excursion, from the simplified compass model CoM excursion equals the linear combination of individual determinants, relying on the idea that each determinant is independent of the others and the effects can be superimposed to predict the total effect. Clinically we know that this is not true as changes in the kinematics of one joint are always accompanied by adaptation in other joints. Another non-linearity is that the amplitude of the CoM excursion is small relative to the lengths associated with the body kinematics. Thus, small errors in the body kinematic measurements can generate noticeable errors in the modeled CoM excursions. These errors are further amplified by the non-linearity of the bodies' geometry where most of the relationships are quadratic in nature. This could come into play because children with CP can have exaggerated joint angles at the extrema of the CoM height.

The assumptions of a compass gait type model are also challenged by the asymmetric gait of an individual with CP. The CoM excursion differs between the steps with the left leg forward and the right leg forward. (In this study we used the average value.). Children with CP often never completely straighten their legs when walking. Thus one must consider whether to use their anatomical leg length or an effective leg length based on constant knee flexion. In addition, the compass gait model assumes that the CoM rocks over an ankle-less leg during stance. However, children with CP may use the forefoot as the pivot over which the CoM rotates resulting in a different effective leg length.

Conclusion

The determinants of gait analysis quantifies the contribution of the lower body kinematics on the vertical excursion of the total body CoM. The determinants of gait analysis suggests that the increased CoM vertical excursion of children with CP is due mainly to a lower CoM minimum because of increased flexion of both legs during double support with a contribution from heel rise during single support. It is important to note that the static analysis of CoM determinants provides limited insight into the mechanics of gait for patients with CP. Since a determinant of gait analysis presents only a static geometric snapshot of gait, it does not elucidate the deeper musculoskeletal causes. Thus at times the effects of individual determinants can be misinterpreted if a more complete dynamic analysis is not conducted.

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Figure 1.

Model I. A modified compass gait model including ipsi-, contra-lateral knee flexion, pelvic rotation, and heel rise is applied at the time instant of minimum CoM height.

Figure 2.

Model II. A modified compass gait model is applied at the time instant of maximum CoM height and includes single support Knee flexion, leg inclination, pelvic obliquity, and single support heel rise.

Figure 3.

Isolated contribution of the gait determinants normalized by the measured total excursion. Positive values reflect a beneficial effect (decrease) on total excursion, negative values reflect a detrimental effect (increase) on total excursion. Significant differences between the two groups are noted (*= $p < 0.05$, **= $p < 0.01$, ***= $p < 0.001$).