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Dynamic stability during walking in children with and without cerebral palsy

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ABSTRACT

Background: Cerebral palsy (CP) is associated with a high risk of falling during walking. Many gait abnormalities associated with CP likely alter foot placement and center of mass (CoM) movement in a way that affects anterior or lateral dynamic stability, in turn influencing fall risk.
Research question: Do children with CP demonstrate altered anterior or lateral dynamic stability compared to typically-developing (TD) children?
Methods: In this case-control, observational study, we measured gait kinematics of two groups of children (15 CP, 11 GMFCS level I, 4 GMFCS level II; 14 TD; age 5–12) in walking conditions of a preferred speed, a fast speed, and a preferred speed while completing a cognitive task. For dominant and non-dominant limbs, the margin of stability (MoS), a spatial measure of dynamic stability, was calculated as the distance between the edge of the base of support and the CoM position after accounting for scaled velocity. Statistical comparisons of were made using mixed factorial ANOVAs. *Post hoc* comparisons were Sidak adjusted.
Results: The anterior MoS before foot strike and at mid-swing differed between each condition but not between groups. Based on the minimum lateral MoS, children with CP had more stability when bearing weight on their non-dominant limb compared to TD children. These differences were not apparent when on the dominant limb.
Significance: This high-functioning group of children with CP exhibited a more conservative lateral stability strategy during walking when bearing weight with the non-dominant limb. This strategy may be protective against lateral falls. We observed no between-group differences in anterior stability. Because CP has been previously associated with impaired anterior balance reactions, and there was no observed compensation in anterior gait stability, this lack of group differences could contribute to a higher risk of falling in that direction.

1. Introduction

Children with cerebral palsy (CP) have a high risk of falling, with 35% of patients reporting daily falls, and an additional 30% reporting monthly or weekly falls [1]. About 55% of these falls occur during walking [2]. Gait abnormalities associated with CP include less knee flexion during swing, knee hyperextension (i.e. recurvatum) or excessive flexion (i.e. crouch) during stance, limited dorsiflexion (i.e. equinus), leg crossing in swing (i.e. scissoring), internal hip rotation, and excessive hip adduction [3]. These abnormalities may alter foot placement and the trajectory of the whole-body center of mass (CoM) such that stability is decreased and, therefore, the risk of falling is increased.

Given the broad use of "stability" in characterizing gait [4], it is important to clearly define the term in the context of this study. Stability has been defined as the "capacity of a system to respond to perturbations" [5], with a stable gait not leading to "falls in spite of perturbations" [4]. These definitions imply that a person's stability during gait is comprised not only of their initial conditions when a perturbation is delivered, but also of their skill in actively responding to that perturbation. While both aspects are relevant to fall risk, this paper is focused on stability as the initial conditions should a perturbation occur

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during walking, with acknowledgement that these conditions are likely influenced by the skill and strategy of responding to internally produced perturbations. We also specifically consider stability in regards to the CoM trajectory relative to the base of support (BoS), an approach based on the inverted pendulum model. Therefore, a "stable" situation implies that a perturbation is needed to initiate a fall in a given direction, and an "unstable" situation implies that some compensatory action, such as a step, an external force, or counter-rotating segments about the CoM [6] is needed to arrest a fall and regain stability.

Previous assessments of children with CP suggest that gait stability is dependent on speed and direction. As measured by step placement relative to a "foot placement estimator," those with CP were *more unstable* anteriorly compared to typically-developing (TD) children, especially at fast speeds and when stepping with the more affected limb [6]. Conversely, children with CP have also demonstrated *more anterior gait stability*, as indicated by smaller inclination angles between the CoM and center of pressure. Slower walking speeds likely contributed to this result [7]. In the frontal plane, the conclusions regarding stability in children with CP have also been inconsistent. Relative to a lateral loss of stability over the stance limb, Bruijn and colleagues [6] determined a less stable gait in children with CP at fast speeds using the foot-placement estimator. Conversely, Chang and colleagues [7] observed more lateral stability (i.e. a larger inclination angle) in children with CP compared to TD children, coinciding with wider steps in the CP group [6,7]. Although not specifically a measure of stability, children with CP have exhibited larger lateral CoM excursions and velocities relative to the center of pressure [8,9], suggesting an altered control of stability.

Although many methods can quantify stability [4], we chose to evaluate the "margin of stability" (MoS). The MoS is the distance between the edge of the BoS and the vertical projection of the extrapolated center of mass, the latter of which is determined from the position and scaled velocity of the CoM [10]. The MoS is advantageously a dynamic measure accounting for velocity that can be evaluated at distinct time points in the gait cycle. Additionally, the MoS magnitude is proportional to the impulse needed to change stability states (i.e. stable or unstable, as represented by positive or negative MoS values, respectively) [10]. Therefore, it has explicit biomechanical meaning and is an ideal indicator of the "initial conditions" of a system should a perturbation occur. Because other stability measures do not meet all of these criteria, we believe the MoS is an ideal biomechanical measure to be used in the context of this study. Previously, the MoS has been used to quantify the stability of young adults [5], older adults [11], persons with multiple sclerosis [12], stroke survivors [13], and persons with Parkinson's disease [14], but not children with CP.

The purpose of this study was to compare the anterior and lateral MoS of children with and without CP at preferred and fast walking speeds and preferred walking speeds with a cognitive task. This latter condition was to provide insight on the executive control of stability maintenance [15–17]. We assessed minimum anterior stability values (i.e. immediately before foot strike), time points when a stumble is likely (i.e. swing limb passing stance limb), and the minimum lateral stability during the stance phase. We hypothesized that (1) children with CP would be less stable than TD children during walking, (2) group differences would be greater when bearing weight with the non-dominant limb, and (3) compared to preferred speeds, group differences would be greater at fast speeds and with a dual task.

2. Materials and methods

2.1. Participants

Fifteen children with spastic CP (10 diplegic, 5 hemiplegic; 6 boys/9 girls; 11 GMFCS level I, 4 GMFCS level II; 5–12 years old, mean (SD) age = 8.7 (2.4) years; BMI 17.0 (2.4) kg m^{-2}) and 14 TD children (7 boys/7 girls; 5–12 years old, age = 9.1 (2.5) years; BMI 16.7 (2.6) kg m^{-2}) participated. Participants were excluded if they reported any diagnosed genetic, cardiovascular, metabolic, skeletal, or neuromuscular disorder (other than CP), or a recent (within one year) injury altering mobility, balance, or safe participation. Participants were also excluded if they presented with acute illness or open lesions, had recent surgeries (within one year) to the lower-extremities, back, or shoulders, used a Baclofen pump, or were unable to follow instructions. All participants could walk without the use of assistive devices. Limb dominance was determined by the self-reported leg preference in kickgin a ball for distance and accuracy (i.e. the "mobilization limb") [18], labeled as the dominant limb. The University of Delaware institutional review board approved this study, and all participants provided informed assent with legal guardians providing informed consent.

2.2. Procedure

Participants were evaluated using the Pediatric Balance Scale (maximum score = 56) [19] as a clinical measure of balance. The trajectories of 41 retroreflective markers on extremities, pelvis, trunk, and head were recorded (Qualisys, Göteborg, Sweden, 120 Hz) as participants walked at self-selected preferred speeds, fast speeds, and preferred speeds with a cognitive task across a 10 m walkway. For the fast condition, participants were instructed to walk as fast as possible without running. All participants completed a minimum of four trials at both preferred and fast speeds. A one-minute continuous walk, including changing directions, with a dual-task activity was also completed. During the dual-task activity, participants attempted to rapidly name as many unique things in a specific category (i.e. foods, names of people, or animals) [20]. We analyzed each straight-line pass through the motion-capture volume.

2.3. Data analysis

The MoS was calculated using custom LabVIEW software (National Instruments, Austin, TX, USA) as follows,

$$MoS = \left(CoM + \frac{Vcom}{\sqrt{\frac{g}{l}}} \right) - BoS$$

where *CoM* is the position and v_{com} is the velocity of the whole-body center of mass in the transverse plane, *g* is gravity (9.81 m s^{-2}), *l* is the instantaneous pendulum length measured from the CoM to the ankle joint center of the stance limb, and BoS is the edge of the base of support, estimated by toe marker position of the stance limb. Stable or unstable conditions were represented by positive or negative MoS values, respectively.

We determined the anterior MoS at key points of interest in the gait cycle (Fig. 1). The *anterior MoS before foot strike* was evaluated to represent the maximum instability allowed during gait. The *anterior MoS at mid-swing*, or the point at which the swing-limb and stance-limb toe markers were even, was chosen to describe stability when a stumble was likely to occur. Lastly, we determined the *minimum lateral MoS* during stance. All stability measures were scaled to body height to account for body size across a range of children [21].

The participant's limb-specific stability measure was averaged from two complete gait cycles from each trial. A mixed factorial ANOVA was conducted to assess the effects of GROUP and CONDITION on observed gait speed scaled by body height. Mixed factorial ANOVAs were used to evaluate the effects and interactions of GROUP (CP or TD), LIMB (dominant or non-dominant), and CONDITION (preferred, fast, or dual task), with effect sizes reported as partial eta squared (η^2). *Post hoc* comparisons were made using Sidak adjustments and reported with estimated means and standard errors of the observed differences. Between-group differences in age, height, body mass, and BMI were assessed using independent *t*-tests and reported with Glass's Δ effect sizes. Significance was determined as $p < 0.05$, and all statistical

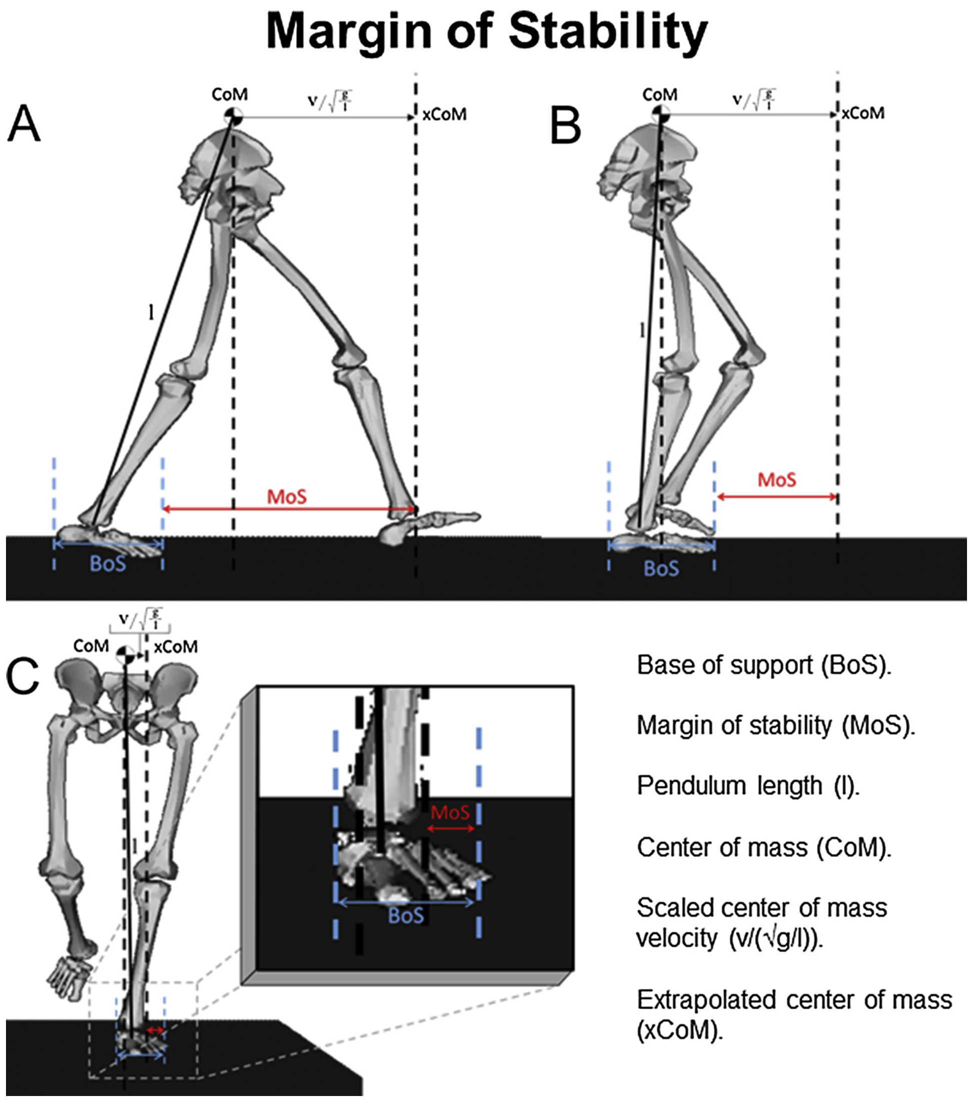

Fig. 1. Illustration of stability measures: (A) anterior margin of stability before foot strike; (B) anterior margin of stability at mid-swing; and (C) minimum lateral margin of stability.

analyses were performed using SPSS software (v25, IBM, Armonk, NY).

3. Results

3.1. Participant demographics

There were no significant differences and only small effects between CP and TD groups in height ($p = 0.47$, Glass's $\Delta = 0.27$, mean difference (SE) of TD-CP = 0.1 (0.1) meters), age ($p = 0.66$, Glass's $\Delta = 0.16$, mean difference (SE) = 0.4 (0.9) years), mass ($p = 0.49$, Glass's $\Delta = 0.22$, mean difference (SE) = 2.5 (3.6) kg), or BMI ($p = 0.74$, Glass's $\Delta = 0.12$, mean difference (SE) = 0.3 (0.9) $kg\,m^{-2}$). The CP group scored lower on the Pediatric Balance Scale ($p = 0.01$, Glass's $\Delta = 4.37$, mean difference (SE) = 1.9 (0.59) points). However, only three CP subjects scored below the age-specific cut-off points (≈53) that suggest low functional balance [19], and eight of these participants scored at or above 55 out of 56.

3.2. Gait speed

The CP and TD groups did not walk at significantly different speeds. A significant CONDITION effect ($p < 0.01$, $\eta^2 = 0.88$) indicated that, compared to preferred speeds, both groups walked faster when instructed to do so ($p < 0.01$, mean difference (SE) = 0.57 (0.04) statures/s) and walked slower during the dual task condition ($p < 0.01$, mean difference (SE) = 0.11 (0.03) statures/s). No significant CONDITION by GROUP interaction ($p = 0.25$, $\eta^2 = 0.05$) or main effect of GROUP ($p = 0.20$, $\eta^2 = 0.06$) was found (Fig. 2).

3.3. Anterior margin of stability before foot strike

The CP and TD groups did not differ in their maximum (most negative/unstable) anterior instability. A significant CONDITION effect ($p < 0.01$, $\eta^2 = 0.89$) revealed that both groups were more stable at the preferred-speed condition ($p < 0.01$, mean difference (SE) = 21.3 (1.5) percent body height (%BH)) compared to the fast-speed condition. Additionally, participants were more stable with a dual task compared to the preferred speed condition ($p < 0.01$, mean difference (SE) = 5.1 (1.0) %BH). There were no significant interactions with GROUP, LIMB, or CONDITION (all $p > 0.09$, $\eta^2 < 0.09$) or main effects of GROUP ($p = 0.10$, $\eta^2 = 0.10$) or LIMB ($p = 0.51$, $\eta^2 = 0.02$) (Fig. 3).

3.4. Anterior margin of stability at mid-swing

The CP and TD groups did not differ in their anterior stability at mid-swing. A significant CONDITION effect ($p < 0.01$, $\eta^2 = 0.82$)

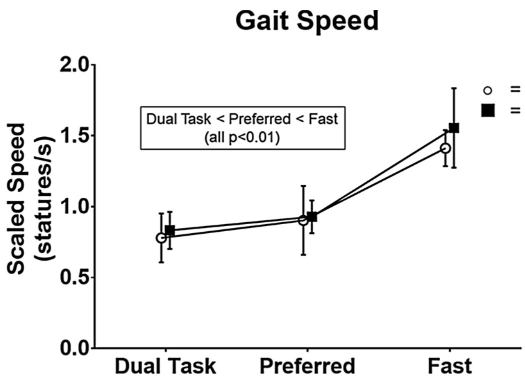

Fig. 2. Gait speed under different conditions and across groups. Open circles represent the cerebral palsy (CP) group. Closed squares represent the typically-developing (TD) group. Compared to preferred speeds, both groups walked faster when instructed to do so ($p < 0.01$) and walked slower during the dual-task condition ($p < 0.01$). No significant differences were observed between groups (CONDITION x GROUP $p = 0.25$, GROUP $p = 0.19$).

revealed that both groups were more stable at the preferred speed condition ($p < 0.01$, mean difference (SE) = 15.7 (1.7) %BH) compared to the fastest speed condition. Additionally, participants were more stable with a dual task compared to the preferred speed condition ($p < 0.01$, mean difference (SE) = 3.6 (0.8) %BH). There were no significant interactions with GROUP, LIMB, or CONDITION (all $p > 0.16$, $\eta^2 < 0.07$) or main effects of GROUP ($p = 0.28$, $\eta^2 = 0.04$) or LIMB ($p = 0.70$, $\eta^2 = 0.01$) (Fig. 4).

3.5. Minimum lateral margin of stability

Limb-specific differences in lateral stability suggested more stability in children with CP compared to TD counterparts. Significant LIMB by GROUP ($p < 0.01$, $\eta^2 = 0.34$) and CONDITION by LIMB ($p = 0.048$, $\eta^2 = 0.11$) interactions were identified. In *post hoc* analyses, children with CP were more stable when bearing weight on the non-dominant limb compared to the TD children also on the non-dominant limb ($p < 0.01$, mean difference (SE) = 1.3 (0.5) %BH). These between-group differences were not significant when bearing weight on the dominant limb ($p = 0.60$, mean difference (SE) = 0.2 (0.4) %BH). No significant *post hoc* differences were identified between conditions on each limb (all $p > 0.21$, mean difference (SE) < 0.3 (0.2) %BH) or between limbs within each condition (all $p > 0.11$, mean difference (SE) < 0.4 (0.2) %BH) (Fig. 5).

4. Discussion

This study compared the anterior and lateral stability of children with and without CP. We hypothesized that children with CP would be less stable than TD children, with group differences exacerbated when bearing weight with the non-dominant limb, at fast speeds, or with a cognitive task. These hypotheses were ultimately not supported by our data, but we did observe a limb-specific, between-group difference in lateral stability. While on the non-dominant limb, in all conditions, children with CP exhibited a *more stable* gait laterally. This result suggests a conservative stability strategy in children with CP that potentially protects against lateral falls. The observation that those with CP had significantly altered lateral stability, but unchanged anterior stability, is reasonable, as frontal plane control requires more active components than control in the sagittal plane [22,23]. The altered neural control in CP likely influences the lateral CoM trajectory relative to the stance limb, lateral step placement, and the response should a lateral perturbation occur.

When considering lateral stability with respect to a fall over the stance limb, this conservative stability strategy employed by children with CP agrees with some previous findings [7], but not others [6]. While specific levels of functionality, such as GMFCS, were not reported for these studies, it is possible that a lower-functioning cohort could not employ this conservative strategy, instead resulting in less stability due to impaired limb control. We suggest using a similar procedure with a lower-functioning cohort to address this hypothesis. Regardless, we encourage consistent reporting of established functional evaluations so that novel biomechanical analyses may be interpreted within the context of current clinical practice.

Lateral stability may be modified through changes in step width, stride frequency, and foot orientation. In follow-up analyses of non-dominant limb kinematics, we observed no between-group differences in step width across conditions (all $p > 0.37$, Glass's $\Delta < 0.31$, mean difference (SE) < 0.01 (0.01) cm). At a constant speed, the lateral MoS of unimpaired adults increases with a higher stride frequency [24]. In children with CP, increasing stride rate is more important than increasing stride length as a means to walk faster [25]. Despite this potential influence of stride rate on stability, we observed no between-group differences in stride rate across conditions ($p > 0.49$, Glass's $\Delta < 0.31$, mean difference (SE) < 0.04 (0.09) strides per second). Significant between-group differences were observed in foot orientation on the non-dominant limb at preferred ($p = 0.02$, Glass's $\Delta = 0.89$, mean difference (SE) = 6.9 (2.7) degrees), fast ($p = 0.01$, Glass's $\Delta = 1.02$, mean difference (SE) = 6.9 (2.4) degrees), and dual-task ($p = 0.05$, Glass's $\Delta = 0.85$, mean difference (SE) = 7.6 (3.7) degrees) conditions. The CP group had larger foot progression angles, placing the toe more lateral relative to the heel. This foot orientation increases the width of the BoS, potentially increasing lateral stability. This observation is interesting, as a previous report of nearly 500 children with CP observed in-toeing (~65%) to be a more prevalent gait abnormality than out-toeing (~25%) [3]. Possibly, a more impaired cohort may not be able to use an out-toeing strategy.

The definition of limb dominance (i.e. the preferred kicking limb) could underlie observed differences in lateral stability. In children with

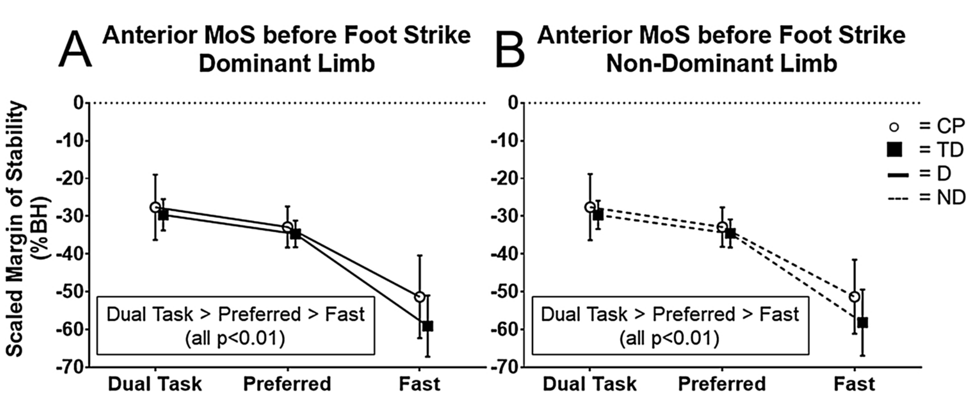

Fig. 3. Anterior margin of stability (MoS) before foot strike under different conditions, across groups, and between limbs. Open circles represent the cerebral palsy (CP) group. Closed squares represent the typically-developing (TD) group. Solid lines represent the dominant (D) limb. Dashed lines represent the non-dominant (ND) limb. Panel A shows the results from the dominant limb. Panel B shows the results from the non-dominant limb. Stable or unstable conditions represented by positive or negative MoS values, respectively. Compared to preferred speeds, both groups were more stable during the dual-task condition ($p < 0.01$) and less stable at fast speeds ($p < 0.01$).

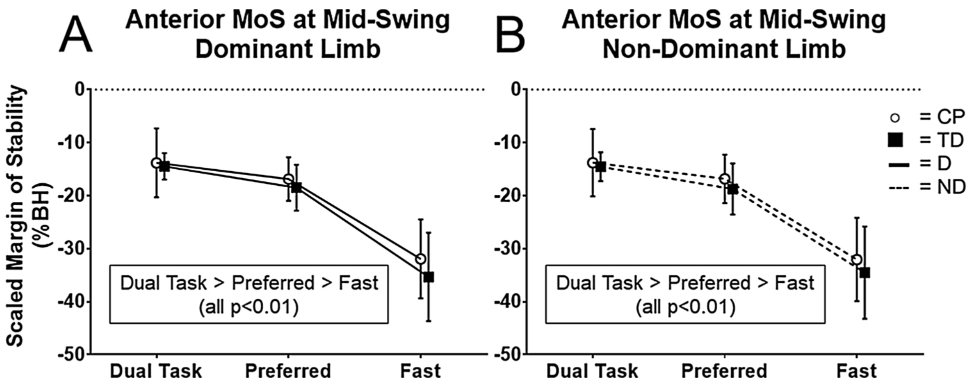

Fig. 4. Anterior margin of stability (MoS) at mid-swing under different conditions, across groups, and between limbs. Open circles represent the cerebral palsy (CP) group. Closed squares represent the typically-developing (TD) group. Solid lines represent the dominant (D) limb. Dashed lines represent the non-dominant (ND) limb. Panel A shows the results from the dominant limb. Panel B shows the results from the non-dominant limb. Stable or unstable conditions represented by positive or negative MoS values, respectively. Compared to preferred speeds, both groups were more stable during the dual-task condition ($p < 0.01$) and less stable at fast speeds ($p < 0.01$).

CP, the dominant limb had less lateral stability (versus non-dominant), whereas in TD children the opposite was observed (Fig. 5). Regarding functional gait asymmetry, it's been proposed that the kicking limb is a "mobilization" limb, while the non-kicking limb plays a "stabilizing" role [18]. The presence of limb impairment due to CP may cause individuals to prioritize one role over the other. In other words, children with CP may prioritize stability during a kicking motion so that their less-impaired limb is the supporting foot. Previous studies have designated limbs as "unaffected" and "affected" in the CP group with ambiguous designations in the TD group [6,8,9]. Based on clinical tests of lower extremity function (SCALE and Ashworth scores), the study physical therapist could not definitively identify a "more affected" limb for many of our CP participants. Therefore, the kicking-limb designation was likely the most appropriate for this study, as it also accounted for left-dominant TD participants. In order to remove this potential confounding influence on limb dominance, an alternative approach would be to separate limbs based on whether they were the *more stable* or *less stable* limb during gait. With this gait-specific approach, we observed a significant GROUP by CONDITION interaction ($p = 0.05$, $\eta^2 = 0.11$). *Post hoc* analyses revealed that children with CP had more lateral stability than TD children in fast ($p = 0.01$, mean difference (SE) = 1.2 (0.5) %BH), but not in preferred or dual task conditions (both $p > 0.14$, mean difference (SE) < 0.7 (0.5) %BH). Given our original analyses and this alternative approach, it is clear that our children with CP had more lateral stability, and it may be that fast walking encourages adoption of that conservative strategy.

Unlike previous studies [6,7], we did not observe between-group differences in anterior stability. From our measures, a less stable gait was associated with faster walking in both groups. Previous studies reported slower gait speed in children with CP than in TD groups walking at preferred and fast speeds [6,25]; however, our study did not show the same differences (Fig. 2). Of note, the previously observed anterior stability differences between groups during fast walking were likely only apparent *after accounting for differences in gait speed* [7, see reference Figure 6]. Therefore, no stability differences would have been observed if gait speed were described categorically, as done in our present study. This observation suggests a hypothesis that stability is a limiting factor in fast walking. In other words, children with CP may not increase gait speed if it results in instability beyond a perceived threshold. Based on the GMFCS levels and Pediatric Balance Scale performance of included subjects, we suspect that our group of children with CP were high functioning, potentially resulting in tempered differences between groups. Regardless, the lack of group differences in anterior stability is worrisome, as the response to anterior perturbations is impaired in children with CP [26,27], including those in this study reported separately [28]. We expected that those with impaired balance reactions would compensate with increased stability during gait. This discrepancy could increase the risk of falling should an anterior perturbation occur during walking.

We did not observe an exaggeration of between-group effects with a dual task. Compared to the preferred speed, both groups slowed during the dual-task activity, as also observed in a post-stroke group [15]. With the significant developmental differences across our age range, it was difficult to assign a dual-task activity that sufficiently challenged each child. Consequently, it is possible that the cognitive task was not sufficiently demanding to induce altered stability in the most-developed participants. To our knowledge, this is the first study to evaluate gait stability during a dual task in children with CP. Although we did not observe hypothesized differences in stability with a dual task, the cognitive demand may alter the ability to react to a perturbation should it occur. This latter aspect warrants further investigation.

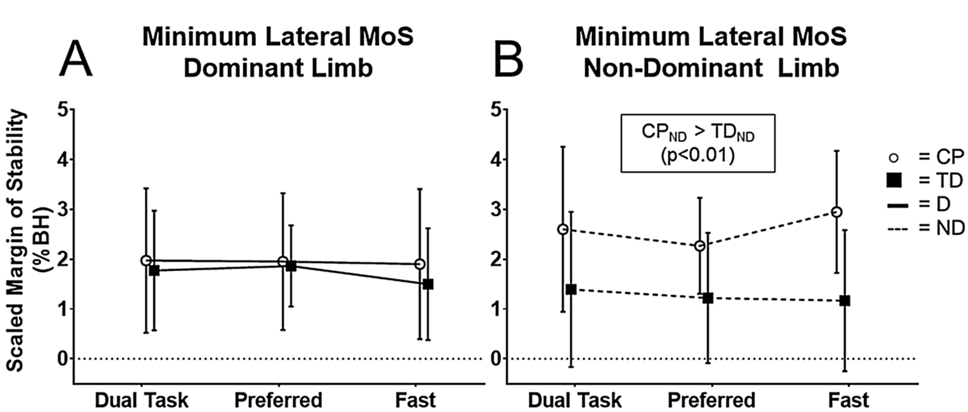

Fig. 5. Minimum lateral margin of stability (MoS) under different conditions, across groups, and between limbs. Open circles represent the cerebral palsy (CP) group. Closed squares represent the typically-developing (TD) group. Solid lines represent the dominant (D) limb. Dashed lines represent the non-dominant (ND) limb. Panel A shows the results from the dominant limb. Panel B shows the results from the non-dominant limb. Stable or unstable conditions represented by positive or negative MoS values, respectively. Children with CP were more stable when bearing weight on the non-dominant limb compared to the TD children also on the non-dominant limb ($p < 0.01$) but no significant differences were identified between limbs at different conditions.

5. Conclusion

A high-functioning group of children with CP, compared to TD controls, exhibited a more conservative lateral stability strategy. This trend was more pronounced when bearing weight with the non-dominant limb or when walking at fast speeds. Despite previously reported affected responses to anterior perturbations [28], we observed no group differences in anterior stability during walking. This discrepancy could increase the risk of falling should an anterior perturbation, such as a trip, occur during walking.

Author contributions

All authors significantly contributed to the formation of this work through project conception, data acquisition, analysis and interpretation of results, and manuscript drafting and revising. All authors provided final approval for submission.

Conflict of interest

The authors declare no financial or personal conflict of interest.

Acknowledgments

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