Bilateral Foot Center of Pressure during Trunk Forward Bending and Reaching

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Abstract

This study analyze bilateral foot center of pressure (CoP) and compare the extent of bilateral lower limb involvements during trunk forward bending and reaching in stroke patients. The measures of limb involvements were maximum CoP displacement in anterior-posterior direction and the proximal and distal ends of the CoP trajectory. Side of foot and target location interaction effects were significant for maximal CoP anterior-posterior displacement. The target location didn’t affect the proximal end of the CoP trajectory neither did it affect the difference between feet. The target location affected the distal end of the CoP trajectory and the CoP maximal anterior-posterior displacement significantly, but only the later parameter showed the difference between feet for specific target locations. The pedeography also show the target effects on CoP and different extent of bilateral limb involvements. The relationship between foot CoP and neuromuscular control needs further investigations.

1. Introduction

Abilities to maintain postural stability depend on multiple system interactions and are affected by both extrinsic and intrinsic factors. Extrinsic factors are those such as environmental constraints, while intrinsic factors are those such as neurological conditions. Stroke is the most common neurological condition that impair postural stability and patients after stroke were found to demonstrate high risk of fall during recovery process. Understanding the control of postural stability during daily voluntary task is necessary for design of balance training programs because most of the falls happened in daily living context.

Trunk forward bending and reaching is a frequent encountered daily context. The location of the target for reaching determines the required amount of center of mass (CoM) shift. As the required amount of CoM shift increases, the demands on the postural control systems increases concurrently. Previous studies found that the postural control features were regulated by the distance for reaching and direction of trunk movements. It was suggested that during forward and backward trunk bending movements, the body CoM is efficiently regulated with respect to the base of support (BoS). Most of the results of those studies suggested that the axial synergy, described as opposing displacements of the trunk and knee segments with those of the hips, acts to minimize the horizontal CoM displacement to prevent instability. Center of gravity (CoG) is the point application of ground reaction force of the CoM and the trajectory of the center of pressure (CoP), though different from the trajectory of CoG, is a reasonable approximation to the trajectory of CoG. Therefore, the present study intended to investigate the postural control features during trunk bending and reaching for targets at various locations by measures of CoP trajectory.

Quantitative spatiotemporal measures of CoP have been repeatedly proven as robust indicators of the quality and functional balance ability during performance of voluntary movement, but describe the outcome of the dysfunction rather than the origin. These measures failed to describe a specific mechanism by which performance and function are increased after rehabilitation. We consider qualitative pattern of CoP to be an outcome of the underlying mechanistic processes. Researchers have used plantar pressure recording devices in various clinical populations to describe the features of posture and gait, but nothing as specific as CoP trajectory under the individual feet during trunk forward bending and reaching has been reported. CoP under individual feet provides information specific to each lower extremity and the neuromotor fluctuations that are part of motor control. Mizelle et al. predicted functional performance by CoP measures under individual feet and suggested that bilateral feet CoP might have the potential to provide information about the underlying control properties of the neuromuscular system.

The purposes of this study were: (1) to investigate the CoP trajectory under the individual feet of stroke patients during trunk forward bending and reaching,
to examine the interactions effects of side of foot and target location and their main effects on individual feet CoP measures, (3) to examine the effects of target locations on CoP measures under the individual feet, (4) to investigate the correlations of the CoP measures between feet, (5) to identify specific individual feet CoP characteristics affected by the target locations. The results of this study could provide suggests for the clinicians in postural control for stroke patients.

2. Methods

Twenty-nine stroke patients signed informed consent form and made 2 bending-and-reaching trials for each of the 6 target locations at their self-selected pace. The target locations were designed by varying the distance and direction in relation to the participants (Fig. 1).

Participants performed all trials while standing on a 0.5m instrumented mat (Footscan, Rsscan pressure measurement system, Belgium) (Fig.2). Pressure-sensitive sensors embedded in the mat were sampled at 100 Hz with a sampling duration of ten seconds. The pressure measurement system is able to export the coordinates of CoP under individual foot and the data were processed to calculate the maximal CoP displacement in anterior-posterior direction (MAP) /foot length ratio (MAP%FL), the position of the proximal end of the CoP trajectory (Start), and the position of the distal end of the CoP trajectory (Stop). (Fig. 3) As shown in figure 3, the pedography could be exported to show qualitatively the e effects of target location on the CoP trajectory and the difference in CoP trajectory between feet.

Figure 2. The six target locations. Number 1–6 indicated the six target locations for. Numbers 1, 3, and 5 are targets at near distance. Number 1, 4, and 6 are targets at far distance. Number1-2 and 5-6 are targets deviated from the middle. Number 3 and 4 are targets in the middle. The lines connecting 1 and 2, 3 and 4, and 5 and 6 originated from the same point which is in the middle of the tips of two great toes. The angle between lines connecting (1, 2) and (3, 4) was 45 degrees, which was the same as the angle between lines connecting (5, 6) and (3, 4).

Figure 2. Pedography for the individual foot during forward bending and reaching in stroke patients. This is a stroke patient with a left hemiplegia and the subject was reaching for a target that located at the “B” position as indicated in Fig. 2. A is the proximal end of CoP and its position is designated as percent of foot length (Start). B is the distal end of CoP and its position is designated as percent of foot length (Stop). The distance between point A and B is the maximum CoP displacement in AP direction and was designated as percent of foot length (MAP%FL).

Two-way repeated-measure analysis of variance was used to examine the interaction of side of foot and target location on CoP measures. The subsequent post hoc analysis, including paired-t test and one-way repeated-measure analysis of variance were used selectively depending on the results of the interaction effects. Pearson correlation coefficient analysis was used to examine the relationship of the CoP measures between feet. The statistical significant level was set at $\alpha = .05$. 

Figure 1. The instrument setup (the pressure at on the top of the AMTI forceplate) and the forward trunk bending and reaching task.
3. Results and discussions

3.1. The position of the proximal end of CoP trajectory (Start)

Non-significant foot and target location interaction effects were found (Table 1, \( p = .099 \)), indicating that the difference of the location of the proximal end of CoP between feet was not influenced by target locations. Either foot or target location main effects were significant (Table 1, \( p = .418 \) for foot main effects, \( p = .265 \) for target location main effects).

The effects of target distance on “Start” were consistent across target directions and across feet (Fig. 4A), while the effects of target directions on “Start” were neither consistent across feet nor consistent across target distances (Fig. 4A). The stroke patients were able to increase the contact areas of both feet with the ground when the distance for reaching increased. However, stroke patients was not able to change the contact area of their paretic feet when the target deviated toward the paretic side.

The CoP shift under the feet has been shown to correlate with the neuromuscular control of the ankle. The above mentioned results suggested that the stroke patients might be able to modulate their ankle control according to target distance and direction, especially the ankle of non-paretic feet. If this holds true, therapist might be able to train the ankle control of stroke patients by involve the stroke patients in reaching activities as described in this study and change the demands on ankle control by varying the target distance and direction. But the clinician should note that extra verbal cuing might be necessary to facilitate the ankle control of paretic feet during reaching. This hypothesis need further experimental testing.

3.2. The position of the distal end of the CoP trajectory (Stop)

Non-significant side of foot and target location interaction effects were found (Table 1, \( p = .076 \)), indicating that the difference in the location of “Stop” between feet was not influenced by target locations. Non-significant foot main effects were found (Table 1, \( p = .273 \)). The descriptive data showed that the distal end of the CoP line of the individual foot located at the position of 60% to 80% foot length, which was within the metatarsal area of the foot (the forefoot area). The location of “Stop” under the paretic feet was farther away from the tip of the toes than that under the non-paretic feet were when reaching for targets at all locations except when reaching for targets on the non-paretic side at both far and near distance (Fig. 4B, 10SS and 30SS). This result suggested that the contact of the forefoot area of the paretic feet were increased but that of the non-paretic feet were decreased by target distance.

Combining the finding of the position of “Start” and the finding of the position of “Stop”, the CoP under the paretic and non-paretic feet was different in two ways: (1) the CoP under the paretic feet were in the midfoot to forefoot area and the CoP under the non-paretic feet was in the hindfoot to forefoot area. (2) the length of the CoP line under the paretic feet and was shorter than that under the non-paretic feet. Those results suggested that the extent of the involvement of the paretic and non-paretic feet during trunk forward bending and reaching were different. The difference might arise from the impaired neuromuscular control of the paretic limb, which decreased the degrees of the participation in weight shifting.

<table>
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<th>DF</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
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<td>.01</td>
<td>2.15</td>
<td>.099</td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
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<td>.008*</td>
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*\( p < .05 \); Abbreviation notations: Start: proximal end of the CoP line under individual feet, Stop: distal end of the CoP line under individual feet; MAP%FL: maximal CoP displacement in anterior-posterior direction normalized to foot length.

Significant target location main effects on the position of the distal end of the CoP line were found (Table 1, \( p < .001 \)). The effects of target distance on the location of “Stop” were consistent across target directions and across feet. Far targets tended to induce the distal end of the CoP line to move closer to the tip of the toes than near targets did (Figure 3) for both feet,
indicating that both the paretic and non-paretic feet were able to increase the forefoot contact with the ground when reaching for far targets. Far targets might be able to facilitate the ankle plantar flexor activation.

The effects of target direction on “Stop” when reaching for near targets were consistent across feet. Both the paretic and non-paretic feet were able to increase the extent of the contact of the forefoot area with the ground when reaching for the targets that was near and in the paretic side (Fig. 4B). In another word, when the target distance remains constant, the targets on the paretic side might be able to induce more muscular activation of foot plantar flexor than targets in the middle and on the non-paretic side.

The effects of target direction on the location of the Stop point when reaching for far targets were not consistent across feet (Fig. 4B). The descriptive data showed that the forefoot area of the foot ipsilateral to the direction of the targets contacted with the ground in a greater extent than that the forefoot area of the foot contra-lateral to the direction of the targets. This is an important implication for the clinicians to induce the participation of the paretic limb by training the CoP shift of the stroke patients with trunk bending and reaching for targets that are far and on the paretic side.

As shown in Fig. 4B, targets that were far and on the paretic side (Fig. 4B, 30AA), were most effective in increasing the foot-ground contact of the paretic foot in stroke patients.

### 3.3. MAP/foot length ratio (MAP%FL)

Significant foot and target location interaction effects on MAP%FL were found (Table 1, \(p = .008\)) and significant foot simple main effects were found for targets that were far and in the middle (Fig.4C, 30M) (Table 2, \(p < .001\)) and for targets that were far and on the paretic side (Fig. 4C, 30AA) (Table 2, \(p = .018\)). The value of MAP%FL was always larger under the non-paretic feet than that under the paretic feet except when the targets were near and on the non-paretic side (Fig. 4C, 10SS). Large MAP%FL indicated larger foot-ground contact area comparing to small MAP%FL. This result suggested that, although that some of the target locations might demand increased involvement of the paretic feet, the stroke patients still are unwilling to use the paretic foot. They might use other compensating movement strategies such as pelvis deviation to manage the increased demands on paretic foot. On the other hand, the targets that were near and on the non-paretic side might be a less challenging task for stroke patients. Therefore, they were confident and willing to increase the involvement of the paretic limbs.

When the participant perceived the level of challenges is too high to manage, inhibition of participation might occur.

![Figure 4. Differences between paretic and non-paretic foot on the position of (A) the proximal end of CoP, (B) the proximal end of CoP, (C) the MAP/Foot length ratio.](image)

The labels of the x-axis represented the location of the target. “M” represents the targets in the middle and is corresponding to the position C/D in figure 2. “AA” represents the targets in the affected side and is corresponding to the position A/B or E/F depending on the side of paresis of the performer. “SS” represents the targets in the non-affected side and is corresponding to the position E/F or A/B depending on the side of non-paresis of the participants. “10” represent the near targets and “30” represents the far targets.

Significant target location simple main effects were found for both paretic and non-paretic feet (Table 3, \(p < .001\)). The post hoc pairwise comparison found that the significant target location effects were found between most of the pairs of target locations for both
feet except the following pairs: 10M vs. 10SS \( (p = .650; p = .164) \), 30M vs. 30AA \( (p = .061; p = .564) \), 30M vs. 30SS \( (p = .146; p = .295) \), and 30AA vs. 30SS \( (p = .772; p = .258) \).

Table 2. Paired-t test summary for analysis of the side of foot simple main effects on MAP/foot length ratio.

<table>
<thead>
<tr>
<th>Target location</th>
<th>Mean SD</th>
<th>SE</th>
<th>M</th>
<th>t</th>
<th>DF</th>
<th>Sig. (2-tailed)</th>
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</thead>
<tbody>
<tr>
<td>10M</td>
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<td>.02</td>
<td>-1.12</td>
<td>29</td>
<td>.272</td>
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<tr>
<td>30M</td>
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<td>.01</td>
<td>-6.64</td>
<td>27</td>
<td>.000*</td>
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<tr>
<td>10AA</td>
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<td>.15</td>
<td>.03</td>
<td>-1.40</td>
<td>29</td>
<td>.172</td>
</tr>
<tr>
<td>30AA</td>
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<td>.13</td>
<td>.02</td>
<td>-2.51</td>
<td>26</td>
<td>.018*</td>
</tr>
<tr>
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<td>.12</td>
<td>.02</td>
<td>-.90</td>
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<td>.378</td>
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<tr>
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<td>.17</td>
<td>.03</td>
<td>-.55</td>
<td>23</td>
<td>.591</td>
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</tbody>
</table>
* \( p < .05 \); Please refer to Table 2 for abbreviation notations.

The MAP%FL of the paretic feet seemed to be influenced by target distances more than by target directions (Fig. 4). The far targets increased the MAP%FL in both paretic and non-paretic feet no matter which direction the targets were at (Fig. 7). This result is consistent with the finding of the proximal and distal end of the COP line. The direction effects on MAP%FL of both feet were consistent across target distance. For the paretic feet, the largest MAP%FL was induced by targets on the non-paretic side and the smallest MAP%FL was induced by the targets in the middle. For the non-paretic feet, targets on the paretic side induced the largest MAP%FL and targets in the non-paretic side always induced the smallest MAP%FL (Fig. 7).

Table 3. Target location simple main effects on MAP/foot length ratio.

<table>
<thead>
<tr>
<th>Target location</th>
<th>Mean SD</th>
<th>SE</th>
<th>M</th>
<th>t</th>
<th>DF</th>
<th>Sig.</th>
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<td>Paretic feet</td>
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<td>.928</td>
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<tr>
<td>Non-paretic</td>
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<td>2.76</td>
<td>.22</td>
<td>17.59</td>
<td>.000</td>
<td>.24</td>
</tr>
</tbody>
</table>
*p < .05

The results showed that the CoP under the non-paretic foot was smoother than the paretic feet and the

3.4. Correlations of CoP measures between feet

Most of the correlations between paretic and non-paretic foot in stroke patients was positive and few was weak when reaching for targets that were far and on the non-paretic side (Table 4). The significant and moderate positive correlation coefficients suggested less than strong synchronized CoP pattern of both feet (Table 4). The significance of involvement of bilateral limbs during dynamic activities is influenced by the asymmetry neuromuscular control in stroke patients. The results also indicated that the target locations influenced bilateral limb synchronization prominently. The synchronization between limbs was the most prominent when the targets were far and in the middle (Table 4, \( r = .81 \)). As the targets deviated away from the middle and toward either the paretic or non-paretic side, the level of synchronizations between limbs decreased.

The correlations between limbs on MAP%FL was weak when reaching for targets that were far and on the non-paretic side (Table 4, \( r = .19 \)) and moderate when the targets were far and on the paretic side (Table 4, \( r = .44 \)). This result further suggested that targets that were far and in the paretic side tended to inhibit the participation of the paretic limb in this task. On the other hand when the targets were in the non-paretic side, more involvement of the non-paretic limb might be induced, and, therefore, the synchronization between limb decreased.

Table 4. Correlation coefficients between paretic and non-paretic foot when reaching for targets at different locations.

<table>
<thead>
<tr>
<th>Target location</th>
<th>10A</th>
<th>30A</th>
<th>10M</th>
<th>30M</th>
<th>10SS</th>
<th>30SS</th>
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<td>-.04</td>
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<td>.19</td>
</tr>
</tbody>
</table>

The bold numbers indicated significant correlations with \( p < .05 \). Please refer to Table 2 for abbreviation notations.

3.5. Qualitative analysis of the CoP trajectory under the individual foot

The results showed that the CoP under the non-paretic foot was smoother than the paretic feet and the
position of the CoP under the non-paretic feet did not change its position within the foot across target location. The position of the CoP under the non-paretic feet was at the midfoot to forefoot area. On the other hand, the CoP under the paretic feet was jerky and affected by the target locations prominently. The position of the CoP under the paretic feet was within the midfoot area and seldom shifts into the forefoot area by with the target locations.

When examining the dynamic pedeograpy in the pressure measurement system, we found that the fluctuation of the CoP under the paretic feet were less prominent than that under the non-paretic feet. Generally speaking, the CoP under the paretic feet moved straight ahead toward the target location and return to the initial position before touched the targets on the floor, while the CoP under the non-paretic feet moved toward the non-paretic side with prominent forth-and-back fluctuations. After finishing the tasks, the CoP under the paretic foot was able to return to the initial position without phase shift, while the CoP under the non-paretic feet shift back toward the initial position at the time when the performer touched the targets on the ground. It seemed that the CoP under the non-paretic feet needed more time to regain stability after finished the reaching process and the point of stability of the CoP under the non-paretic feet tended to shift toward the non-paretic side in relation to the initial position of the CoP. The CoP shift direction under the paretic and non-paretic feet in the frontal plane was inverse, indicating that the movement strategies in both feet was reciprocal. The reason for these reciprocal movement strategies might be for equilibrium maintenance.

The CoP shift direction of the paretic and non-paretic feet in the sagittal plane indicated that the CoP under the paretic feet shift posterior first, while the CoP under the non-paretic feet did not, indicating that, although the reaching was a forward reaching in nature, the latency for the CoP of the paretic feet to shift anteriorly was observed as an instinct characteristic, especially when the targets were far and on the paretic side (30AA). This might indicate that the location of 30AA might demand an exceptionally amount of CoP shift in anterior direction. The CoP seemed to prepare to return to the initial position before the targets were reached. On the other hand, the paretic feet imitated shift without latency and traveled straightly anteriorly. The CoP under the non-paretic foot seemed to prepare to recover back to the initial position after the targets were touch. The phase shift of the final position of the CoP under the non-paretic feet was prominent and it fluctuated more than that under the paretic feet.

4. Conclusions

The results of this study showed that the bilateral limb involvement during WBR was influenced by the target locations for stroke patients. The most sensitive parameters during reaching to show the difference between feet was MAP%FL.

The distance effects on stroke patients were more consistent across feet than the direction effects. Stroke patients were more capable to manage the increased demands on postural control based on the increased of targets distance than based on the changes of target directions. The correlations between feet were weak to moderate in stroke patients, indicating out-of-phase interlimb control in stroke patients. Far distance induced more interlimb control.

5. References