Short communication

Associations between trunk postural control in walking and unstable sitting at various levels of task demand

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ABSTRACT

Trunk postural control (TPC) has been investigated in several populations and tasks. Previous work observed targeted training of TPC via isolated trunk control tasks may improve performance in other activities (e.g., walking). However, the nature of this relationship remains unknown. We therefore investigated the relationship between TPC, at both the global (i.e., response to finite perturbations) and local (i.e., resistance to continuous perturbations) levels, during walking and unstable sitting, both at varying levels of task demand. Thirteen individuals (11 Male, 2 Female) with no recent history (past 12 months) of illness, injury, or musculoskeletal disorders walked on a dual-belt treadmill at four speeds (20%, 10%, +10%, and +20% of self-selected walking speed) and completed an unstable sitting task at four levels of chair instability (100, 75, 60, and 45% of an individual’s “neutral” stability as defined by the gravitational gradient). Three-dimensional trunk and pelvic kinematics were collected. Tri-planar Lyapunov exponents and sample entropy characterized local TPC. Global TPC was characterized by ranges of motion and, for seated trials, metrics derived from center-of-pressure time series (i.e., path length, 95% confidence ellipse area, mean velocity, and RMS position). No strong or significant correlations (0.057 < p < 0.206) were observed between local TPC during walking and unstable sitting tasks. However, global TPC declined in both walking and unstable sitting as task demand increased, with a moderate inter-task relationship (0.336 < p < 0.544). While the mechanisms regulating local TPC are inherently different, global TPC may be similarly regulated across both tasks, supporting future translation of improvements in TPC between tasks.

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1. Introduction

Physical pathologies including stroke (Verheyden et al., 2006), lower limb loss (Hendershot and Nussbaum, 2013), and low back pain (Lamoth et al., 2006) can adversely influence trunk postural control (TPC). While TPC has been studied extensively, reported measures vary between tasks and specific features of dynamic systems (i.e., global and local). Here, we consider global TPC as the ability of a system to respond to finite (“global”) perturbations (e.g., slip or trip), while local TPC is the ability to resist infinitesimal (“local”) perturbations (e.g., natural gait fluctuations). During gait, global TPC has been indirectly quantified by characterizing segmental motions, such as trunk position variability (Dingwell and Marin, 2006) and ranges of motion (ROM). Meanwhile, nonlinear measures, including Lyapunov exponents (Asgari et al., 2015, Dingwell and Marin, 2006) and sample entropy (SampEn; Lamoth et al., 2010), have characterized local TPC. During unstable sitting, global TPC is often characterized using metrics derived from center-of-pressure (CoP) time series (Hendershot and Nussbaum, 2013; Radebold et al., 2001) and ROM (Larivière et al., 2015); while local TPC has also been characterized by nonlinear analyses of CoP (Larivière et al., 2015; Van Dieën et al., 2010). In both walking and unstable sitting, TPC generally declines with increasing task demand as evidenced by larger values of TPC measures described previously (Dingwell and Marin, 2006; Radebold et al., 2001).
Altered TPC can adversely influence performance in functional activities (e.g., walking), particularly given the relative mass and position of the trunk. Indeed, TPC deficits are associated with an increased risk of falls (Grimbergen et al., 2008, Tinetti et al., 1988) and musculoskeletal injury (Zazulak et al., 2007). Trunk-specific exercise regimens are therefore often proposed or utilized to help mitigate these risks and, in populations with impaired TPC, incorporated into rehabilitation efforts (e.g., Karthikbabu et al., 2011). Such isolated TPC tasks have been shown to reduce pain and functional disability scores in individuals with LBP (O’Sullivan et al., 1997, Carpes et al., 2008) and improve gait parameters in patients after stroke (Karthikbabu et al., 2011). These observations suggest that improvements to TPC may translate between tasks, but there remains a limited understanding of the effectiveness of such rehabilitation paradigms since the relationship between TPC mechanisms in isolated (e.g., unstable sitting) and functional (e.g., walking) activities has not been investigated thoroughly. Evidence comparing local TPC in two upright tasks (standing and walking) observed little-to-no correlation between them (Kang and Dingwell, 2006). However, only a single level of demand was investigated, and TPC during an isolated task (i.e., unstable sitting) was not determined. We thus explored the relationships between TPC during two distinct tasks, walking and unstable sitting, when both are performed at varying levels of task demand. As TPC has been observed to decrease with increasing demand in both tasks, we hypothesized that increases in respective task demands of walking and unstable sitting would be similarly reflected in decrements to TPC, as evidenced by strong inter-task correlations among TPC measures at each level of demand.

2. Methods

2.1. Study design and procedures

Thirteen participants with no current or recent history of illness, injury, or musculoskeletal disorders within the past 12 months (Table 1) completed walking and unstable sitting trials at varying demand levels. For walking trials, participants walked on an instrumented dual-belt treadmill (Bertec, Columbus, OH) at four speeds relative to self-selected walking speed (SSWS; Table 1), determined from the mean velocity of five over-ground trials across a 15 m walkway. For unstable sitting trials, the first and last five trials were analyzed and resampled to 101 points per stride (i.e., 0–100% gait cycle). For unstable sitting trials, the first and last five seconds of data were removed to account for initial and anticipatory adjustments respectively.

2.2. Pre-processing

Data were analyzed using Visual3D (C-motion, Germantown, MD) and MATLAB (Mathworks, Natick, MA). Kinematic and kinetic data were low-pass filtered (Butterworth, 4th order, cut-off frequencies 6 and 10 Hz, respectively). Three-dimensional trunk angles (relative to pelvis) were determined using 6DOF inverse dynamics in Visual3D. For each walking trial, 75 strides of data were analyzed and resampled to 101 points per stride (i.e., 0–100% gait cycle). For unstable sitting trials, the first and last five seconds of data were removed to account for initial and anticipatory adjustments respectively.

2.3. Global TPC analyses

For both tasks, tri-planar trunk-pelvic ROM were determined. Though ROM does not directly quantify global TPC (i.e., response to a perturbation), increases in trunk ROM have been observed in populations with impaired TPC such as fall-prone populations (Tinetti et al., 1988, Grimbergen et al., 2008). Thus, though participants were not perturbed in the current protocol, ROM provided an indirect characterization of global TPC. For seated trials CoP path length, mean velocity, 95% confidence ellipse area (CEA), and RMS positions in the anteroposterior and mediolateral directions were also determined (Prieto et al., 1996).

2.4. Local TPC analysis

Maximum short-term Lyapunov exponents ($\lambda_s$; Rosenstein et al., 1993) and SampEn (Richman and Moorman, 2000) were used to characterize local stability of trunk-pelvic angles. $\lambda_s$ quantifies the rate of convergence/divergence of initially neighboring trajectories. Negative and positive $\lambda_s$ values respectively indicate convergence (i.e., stability) and divergence (i.e., instability); larger positive values represent a decreased ability to resist local perturbations (i.e., decreased local TPC). Here, tri-planar $\lambda_s$ were calculated via state spaces reconstructed from trunk-pelvic angles and their time-delayed copies (Dingwell et al., 2001). Global false nearest neighbor and mutual average information analyses respectively determined embedding dimensions ($m = 6$) and time delays ($\tau = 10$ and $\tau = 100$ samples for walking and seated conditions, respectively).

Unlike $\lambda_s$, SampEn does not directly characterize the response to local perturbations. Rather, it characterizes the prevalence of local perturbations within the system by quantifying its regularity (Richman and Moorman, 2000). Larger values of SampEn indicate

Table 1
Mean (standard deviation) participant demographic information and self-selected walking speeds (SSWS).

<table>
<thead>
<tr>
<th>N</th>
<th>Age (years)</th>
<th>Stature (cm)</th>
<th>Mass (kg)</th>
<th>SSWS (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13(11 M, 2 F)</td>
<td>28.7 (7.2)</td>
<td>177.1 (6.3)</td>
<td>74.6 (11.4)</td>
<td>1.46 (0.18)</td>
</tr>
</tbody>
</table>
low regularity (i.e., high prevalence of local perturbations) while lower values indicate high regularity (i.e., low prevalence of local perturbations). Similar to $\lambda_s$, SampEn was determined via state-spaces reconstructed from trunk-pelvic angles. For SampEn calculations, state-spaces were reconstructed with $m = 2$ (Yentes et al., 2013).

2.5. Statistical analyses

Single-factor, repeated-measures ANOVAs (SPSS Inc., Chicago, IL) assessed the effect of task demand (i.e., speed or $\% VG$) on each outcome measure, with significance concluded when $P < 0.05$. Linear correlation analyses related local and global TPC measures between tasks (e.g., $m \lambda_s$, walking vs. $\lambda_s$, seated) using Spearman's rho ($\rho$) as data were not normally distributed. Correlation strength was assessed qualitatively (Portney and Watkins, 2009): 0–0.25 (little or no relationship), 0.25–0.50 (weak-moderate), 0.50–0.75 (moderate-strong), and >0.75 (strong-excellent).

3. Results

3.1. Walking

$\lambda_s$ increased with increasing walking speed in all planes (Table 2). SampEn increased with speed in the sagittal and transverse planes. Although only approaching significance, SampEn also increased in the frontal plane. Sagittal and frontal plane trunk-pelvic ROM were similar between speeds, but transverse plane ROM increased with walking speed.

3.2. Unstable sitting

All CoP-based metrics were inversely related with $\% VG$. In all planes, $\lambda_s$ remained similar across $\% VG$ levels. While not statistically significant, SampEn tended to decrease with $\% VG$ in the transverse plane. Decreasing $\% VG$ led to increased sagittal and frontal plane ROM (Table 2).

3.3. Correlation analyses

No strong or significant inter-task correlations were observed in local TPC measures (i.e., SampEn and $\lambda_s$). However, measures of global TPC were weakly-to-moderately correlated (Fig. 1). Transverse plane ROM while walking was correlated with sagittal ($p = 0.424$, $P = 0.002$) and frontal plane ($p = 0.433$, $P = 0.001$) ROM, CEA ($p = 0.527$, $P < 0.001$), and both anteroposterior ($p = 0.470$, $P < 0.001$) and mediolateral ($p = 0.544$, $P < 0.001$) RMS positions while seated. Frontal plane ROM while walking was correlated with frontal plane ROM ($p = 0.345$, $P = 0.012$), CEA ($p = 0.336$, $P = 0.015$) and mediolateral RMS position ($p = 0.417$, $P = 0.002$) while seated. Although sagittal plane ROM while walking was not correlated with seated ROM in any plane, it was weakly correlated with mediolateral RMS position ($p = 0.382$, $P = 0.005$) while seated.

4. Discussion

Increases in $\lambda_s$, SampEn, and transverse plane trunk ROM with increased walking speed are consistent with previous work (Asgari et al., 2015, Dingwell and Marin, 2006, Lamoth et al., 2010, Van Emmerik et al., 2005), and suggest both local and global TPC declines with increasing task demand. Specifically, the increases in $\lambda_s$ and SampEn suggest that as walking speed increased, participants became less able to resist local perturbations while simultaneously experiencing more of these perturbations. During unstable sitting trials, the increases in CoP-based measures with decreased chair stability are also consistent with prior reports (e.g., Radebold et al., 2001) and suggest that global TPC declines with increasing task demand during unstable sitting.

Table 2

Mean (standard deviation) ranges of motion (ROM), maximum short-term Lyapunov exponents ($\lambda_s$), sample entropy (SampEn), and CoP-based metrics for walking and unstable sitting conditions (SSWS = self-selected walking speed; VG = gravitational gradient, AP = anteroposterior, ML = mediolateral, VT = vertical). Asterisks (*) indicate a significant effect of task demand ($P < 0.05$).

<table>
<thead>
<tr>
<th>Walking</th>
<th>20% SSWS</th>
<th>10% SSWS</th>
<th>+10% SSWS</th>
<th>+20% SSWS</th>
<th>$F_{(1,48)}$</th>
<th>$P$</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM AP (degrees)</td>
<td>10.5 (4.5)</td>
<td>10.23 (3.5)</td>
<td>10.7 (3.1)</td>
<td>11.0 (3.4)</td>
<td>0.174</td>
<td>0.914</td>
<td>0.011</td>
</tr>
<tr>
<td>ROM ML (degrees)</td>
<td>16.4 (4.5)</td>
<td>17.63 (5.8)</td>
<td>20.3 (5.4)</td>
<td>22.5 (7.9)</td>
<td>5.057</td>
<td>0.004</td>
<td>0.240</td>
</tr>
<tr>
<td>$\lambda_s$ AP</td>
<td>1.27 (0.09)</td>
<td>1.31 (0.10)</td>
<td>1.37 (0.15)</td>
<td>1.44 (0.09)</td>
<td>5.333</td>
<td>0.003</td>
<td>0.250</td>
</tr>
<tr>
<td>$\lambda_s$ ML</td>
<td>1.04 (0.11)</td>
<td>1.10 (0.13)</td>
<td>1.18 (0.16)</td>
<td>1.28 (0.20)</td>
<td>6.116</td>
<td>0.001</td>
<td>0.278</td>
</tr>
<tr>
<td>$\lambda_s$ VT</td>
<td>1.17 (0.15)</td>
<td>1.27 (0.15)</td>
<td>1.30 (0.12)</td>
<td>1.38 (0.14)</td>
<td>4.880</td>
<td>0.005</td>
<td>0.234</td>
</tr>
<tr>
<td>SampEn AP</td>
<td>0.27 (0.06)</td>
<td>0.28 (0.06)</td>
<td>0.33 (0.08)</td>
<td>0.35 (0.08)</td>
<td>4.401</td>
<td>0.008</td>
<td>0.216</td>
</tr>
<tr>
<td>SampEn ML</td>
<td>0.22 (0.04)</td>
<td>0.23 (0.04)</td>
<td>0.24 (0.04)</td>
<td>0.26 (0.04)</td>
<td>2.708</td>
<td>0.056</td>
<td>0.145</td>
</tr>
<tr>
<td>SampEn VT</td>
<td>0.17 (0.03)</td>
<td>0.18 (0.04)</td>
<td>0.21 (0.04)</td>
<td>0.23 (0.04)</td>
<td>7.349</td>
<td>&lt;0.001</td>
<td>0.315</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unstable Sitting</th>
<th>100% VG</th>
<th>75% VG</th>
<th>60% VG</th>
<th>45% VG</th>
<th>$F_{(1,48)}$</th>
<th>$P$</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM AP (degrees)</td>
<td>3.8 (2.7)</td>
<td>5.5 (3.20)</td>
<td>5.6 (2.6)</td>
<td>8.4 (3.2)</td>
<td>5.127</td>
<td>0.004</td>
<td>0.243</td>
</tr>
<tr>
<td>ROM ML (degrees)</td>
<td>1.8 (1.1)</td>
<td>2.0 (1.7)</td>
<td>2.4 (1.2)</td>
<td>4.5 (1.0)</td>
<td>19.457</td>
<td>&lt;0.001</td>
<td>0.549</td>
</tr>
<tr>
<td>$\lambda_s$ AP</td>
<td>0.12 (0.06)</td>
<td>0.10 (0.04)</td>
<td>0.10 (0.02)</td>
<td>0.09 (0.02)</td>
<td>1.235</td>
<td>0.307</td>
<td>0.072</td>
</tr>
<tr>
<td>$\lambda_s$ ML</td>
<td>0.11 (0.04)</td>
<td>0.09 (0.04)</td>
<td>0.11 (0.04)</td>
<td>0.10 (0.03)</td>
<td>0.657</td>
<td>0.583</td>
<td>0.039</td>
</tr>
<tr>
<td>$\lambda_s$ VT</td>
<td>0.13 (0.03)</td>
<td>0.12 (0.04)</td>
<td>0.10 (0.04)</td>
<td>0.11 (0.02)</td>
<td>1.987</td>
<td>0.128</td>
<td>0.110</td>
</tr>
<tr>
<td>SampEn AP</td>
<td>0.05 (0.03)</td>
<td>0.05 (0.02)</td>
<td>0.06 (0.02)</td>
<td>0.06 (0.04)</td>
<td>0.656</td>
<td>0.583</td>
<td>0.039</td>
</tr>
<tr>
<td>SampEn ML</td>
<td>0.04 (0.02)</td>
<td>0.04 (0.02)</td>
<td>0.05 (0.02)</td>
<td>0.04 (0.02)</td>
<td>0.783</td>
<td>0.784</td>
<td>0.220</td>
</tr>
<tr>
<td>SampEn VT</td>
<td>0.04 (0.02)</td>
<td>0.07 (0.02)</td>
<td>0.06 (0.04)</td>
<td>0.04 (0.02)</td>
<td>2.276</td>
<td>0.092</td>
<td>0.124</td>
</tr>
<tr>
<td>Path Length (cm)</td>
<td>43.66 (12.27)</td>
<td>45.49 (11.13)</td>
<td>61.90 (19.72)</td>
<td>84.74 (17.79)</td>
<td>15.498</td>
<td>&lt;0.001</td>
<td>0.569</td>
</tr>
<tr>
<td>Mean Velocity (cm/s)</td>
<td>0.84 (0.48)</td>
<td>1.21 (0.59)</td>
<td>2.84 (1.95)</td>
<td>5.26 (2.77)</td>
<td>9.051</td>
<td>&lt;0.001</td>
<td>0.492</td>
</tr>
<tr>
<td>95% CEA (cm²)</td>
<td>0.84 (0.26)</td>
<td>0.87 (0.19)</td>
<td>1.17 (0.35)</td>
<td>1.62 (0.34)</td>
<td>18.221</td>
<td>&lt;0.001</td>
<td>0.361</td>
</tr>
<tr>
<td>RMS AP (cm)</td>
<td>0.26 (0.07)</td>
<td>0.34 (0.12)</td>
<td>0.47 (0.15)</td>
<td>0.61 (0.14)</td>
<td>18.221</td>
<td>&lt;0.001</td>
<td>0.322</td>
</tr>
<tr>
<td>RMS ML (cm)</td>
<td>0.18 (0.09)</td>
<td>0.20 (0.06)</td>
<td>0.31 (0.11)</td>
<td>0.46 (0.15)</td>
<td>21.614</td>
<td>&lt;0.001</td>
<td>0.575</td>
</tr>
</tbody>
</table>

$\eta^2$: small = 0.01, medium = 0.06, large = 0.14 (Cohen 1988).
However, no significant differences were observed in non-linear metrics between levels of instability in seated conditions suggesting local TPC was not affected by increases in task demand. Moreover, and contrary to our hypothesis, no strong correlations were observed between non-linear TPC measures of walking and unstable sitting, suggesting that local TPC mechanisms differ between seated and walking tasks. This is likely due to the relatively static nature of sitting (vs. walking), evidenced by smaller ROM. Furthermore, while the unstable sitting task required dynamic movements to correct for global perturbations, local perturbations and fluctuations of movement were less prominent given the ultimate goal to remain “still”, likely leading to increased local TPC (i.e., smaller $\lambda_s$ and SampEn) regardless of demand (Table 2). Prior work observed similar results when comparing local stability in static and dynamic tasks (Kang and Dingwell, 2006).

Notably, non-linear metrics exhibited higher variance in seated versus walking tasks. Coefficients of variation for these metrics while walking were 6–24%, and in sitting were 23–64%; high inter-subject variability in the latter was perhaps due to task novelty. Participants may thus have adopted different strategies while adapting to the unstable sitting task, possibly contributing to poor inter-task correlations. Additionally, treadmill (vs. overground) walking can artificially reduce $\lambda_s$ (Dingwell et al., 2001). Changes in gait parameters also persist for five minutes while acclimating to a dual-belt treadmill (Zeni and Higginson, 2010). Our relatively short acclimation period may therefore have influenced trunk kinematics, though all trials were performed under the same conditions and no order effects were observed ($P > 0.301$).

While transverse plane ROM during unstable sitting remained similar across task demands, this may be a result of the unstable chair design. The springs mounted beneath the chair, while allowing for the control of instability level, also limit rotations about the vertical axis. Future work could therefore consider using an apparatus that allows for tri-axial rotations (Van Daele et al., 2009). Additionally, although moderate inter-task correlations were observed, future work could also investigate more “extreme” levels (or spacing) of task demand to further assess this relationship.

Despite little evidence relating local TPC in walking and unstable sitting, recent work suggests that a relationship between global TPC mechanisms exists between tasks. Persons with LBP reported decreased pain and functional disability scores after targeted TPC training (Carpes et al., 2008, O’Sullivan et al., 1997) with changes persisting in a 30-week follow-up (O’Sullivan et al., 1997). Trunk-specific training has improved gait parameters (e.g., gait speed, symmetry, etc.) and functional outcomes in patients post-stroke (Karthikbabu et al., 2011), with more pronounced improvements when trunk-specific exercises were performed on an unstable (versus stable) surface (Karthikbabu et al., 2011, Jung et al., 2016). These results, along with the positive correlations among global TPC measures in the present study, establish a tentative relationship by which improvements in TPC via unstable sitting may translate to other functional activities, though it is presently unclear if this relationship persists among individuals with impaired TPC.

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Conflict of Interest

The authors have no financial or personal relationships with other persons or organizations that might appropriately influence our work presented herein.

References


