Journal of Biomechanics 75 (2018) 181–185

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

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

Julian C. Acasio [a], Courtney M. Butowicz [a], Pawel R. Golyski [a], Maury A. Nussbaum [b], Brad D. Hendershot [a,c,d,*]

[a] *Research & Development Section, Department of Rehabilitation, Walter Reed National Military Medical Center, United States*
[b] *Department of Industrial and Systems Engineering, Virginia Tech, United States*
[c] *DoD-VA Extremity Trauma and Amputation Center of Excellence, United States*
[d] *Department of Rehabilitation Medicine, Uniformed Services University of the Health Sciences, United States*

ARTICLE INFO

Article history:
Accepted 3 May 2018

Keywords:
Center of pressure
Sample entropy
Lyapunov exponents
Biomechanics
Trunk stability

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 ($-0.057 < \rho < 0.206$) 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 ($0.336 < \rho < 0.544$). 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.

Published by Elsevier Ltd.

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).

---

* Corresponding author at: Extremity Trauma and Amputation Center of Excellence, Walter Reed National Military Medical Center, 4494 N. Palmer Road, Bethesda, MD 20889, United States.

E-mail address: bradford.d.hendershot2.civ@mail.mil (B.D. Hendershot).

https://doi.org/10.1016/j.jbiomech.2018.05.006
0021-9290/Published by Elsevier Ltd.

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: −20%, −10%, +10%, and +20% SSWS. Relative (vs. absolute) speeds were chosen to better normalize task demand across participants, with the expectation that faster speeds increase demand (Dingwell and Marin, 2006). At each speed, a 30-s acclimation period was provided before two minutes of data collection. For seated trials, participants sat on an unstable chair (Hendershot and Nussbaum, 2013) with eyes open at four levels of instability, relative to an individual's gravitational gradient (∇G): 100, 75, 60, and 45% ∇G (with instability increasing as %∇G decreased). ∇G was calculated using previously established methods (Slota et al., 2008) and determined neutral seated stability. Participants completed four 60-s trials per condition. However, only the final (i.e., fourth) trial was used for data analyses; the prior three practice trials were used to attenuate learning effects (Van Daele et al., 2007). By the final trial, all participants successfully completed the unstable sitting task (i.e., the seat did not contact the base of support). Participants were asked to keep the chair level and arms crossed throughout trials.

An 18-camera motion capture system (Qualisys, Göteborg, Sweden) collected (120 Hz) 10 surface-marker locations to estimate three-dimensional trunk and pelvic kinematics for all tasks. Markers were placed over the T10 and C7 spinous processes, sternal notch, xiphoid, and bilaterally over the acromion, ASIS, and PSIS. During seated trials, kinetic data were collected (1200 Hz) using a force platform (AMTI, OR6-7-2000, Watertown, MA) mounted beneath the chair. Task and condition order were randomized and counterbalanced, respectively, with 60-s rests provided between trials. Prior to data collection, participants gave informed consent to protocols approved by the local Institutional Review Board.

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 (λ_s; Rosenstein et al., 1993) and SampEn (Richman and Moorman, 2000) were used to characterize local stability of trunk-pelvic angles. λ_s quantifies the rate of convergence/divergence of initially neighboring trajectories. Negative and positive λ_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 λ_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 λ_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).

N	Age (years)	Stature (cm)	Mass (kg)	SSWS (m/s)
13 (11 M, 2 F)	28.7 (7.2)	177.1 (6.3)	74.6 (11.4)	1.46 (0.18)

low regularity (i.e., high prevalence of local perturbations) while lower values indicate high regularity (i.e., low prevalence of local perturbations). Similar to λ_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 %∇G) 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 (ρ) 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

λ_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 %∇G. In all planes, λ_s remained similar across %∇G levels. While not statistically significant, SampEn tended to decrease with %∇G in the transverse plane. Decreasing %∇G 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 λ_s). However, measures of global TPC were weakly-to-moderately correlated (Fig. 1). Transverse plane ROM while walking was correlated with sagittal ($\rho = 0.424$, $P = 0.002$) and frontal plane ($\rho = 0.433$, $P = 0.001$) ROM, CEA ($\rho = 0.527$, $P < 0.001$), and both anteroposterior ($\rho = 0.470$, $P < 0.001$) and mediolateral ($\rho = 0.544$, $P < 0.001$) RMS positions while seated. Frontal plane ROM while walking was correlated with frontal plane ROM ($\rho = 0.345$, $P = 0.012$), CEA ($\rho = 0.336$, $P = 0.015$) and mediolateral RMS position ($\rho = 0.417$, $P = 0.002$) 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 ($\rho = 0.382$, $P = 0.005$) while seated.

4. Discussion

Increases in λ_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 λ_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 (λ_s), sample entropy (SampEn), and CoP-based metrics for walking and unstable sitting conditions (SSWS = self-selected walking speed; ∇G = gravitational gradient, AP = anteroposterior, ML = mediolateral, VT = vertical). Asterisks (*) indicate a significant effect of task demand ($P < 0.05$).

Walking							
	−20% SSW	−10% SSW	+10% SSW	+20% SSW	$F_{(3,48)}$	P	η^2
ROM AP (degrees)	10.6 (4.5)	10.23 (3.5)	10.7 (3.1)	11.0 (3.4)	0.174	0.914	0.011
ROM ML (degrees)	16.3 (4.3)	16.82 (4.5)	18.8 (4.8)	18.7 (4.2)	1.448	0.241	0.083
ROM VT (degrees)	16.4 (4.5)	17.63 (5.8)	20.3 (5.4)	22.5 (7.9)	5.057	0.004^*	0.240
λ_s AP	1.27 (0.09)	1.31 (0.10)	1.37 (0.15)	1.44 (0.09)	5.333	0.003^*	0.250
λs ML	1.04 (0.11)	1.10 (0.13)	1.18 (0.16)	1.28 (0.20)	6.116	0.001^*	0.278
λs VT	1.17 (0.15)	1.27 (0.15)	1.30 (0.12)	1.38 (0.14)	4.880	0.005^*	0.234
SampEn AP	0.27 (0.06)	0.28 (0.06)	0.33 (0.08)	0.35 (0.08)	4.401	0.008^*	0.216
SampEn ML	0.22 (0.04)	0.23 (0.04)	0.24 (0.04)	0.26 (0.04)	2.708	0.056	0.145
SampEn VT	0.17 (0.03)	0.18 (0.04)	0.21 (0.04)	0.23 (0.04)	7.349	$<0.001^*$	0.315
Unstable Sitting							
	100% ∇G	75% ∇G	60% ∇G	45% ∇G	$F_{(3,48)}$	P	η^2
ROM AP (degrees)	3.8 (2.7)	5.5 (3.20)	5.6 (2.6)	8.4 (3.2)	5.127	0.004^*	0.243
ROM ML (degrees)	1.8 (1.1)	2.0 (0.7)	2.4 (1.2)	4.5 (1.0)	19.457	$<0.001^*$	0.549
ROM VT (degrees)	2.8 (1.9)	2.5 (0.6)	2.6 (1.0)	3.3 (1.3)	0.993	0.404	0.058
λ_s AP	0.12 (0.06)	0.10 (0.04)	0.10 (0.02)	0.09 (0.02)	1.235	0.307	0.072
λs ML	0.11 (0.04)	0.09 (0.04)	0.11 (0.04)	0.10 (0.03)	0.657	0.583	0.039
λs VT	0.13 (0.03)	0.12 (0.04)	0.10 (0.04)	0.11 (0.02)	1.987	0.128	0.110
SampEn AP	0.05 (0.03)	0.05 (0.02)	0.06 (0.02)	0.06 (0.04)	0.656	0.583	0.039
SampEn ML	0.04 (0.02)	0.04 (0.02)	0.05 (0.02)	0.04 (0.02)	0.783	0.784	0.220
SampEn VT	0.04 (0.02)	0.07 (0.02)	0.06 (0.04)	0.04 (0.02)	2.276	0.092	0.124
Path Length (cm)	43.66 (12.27)	45.49 (11.13)	61.90 (19.72)	84.74 (17.79)	15.498	$<0.001^*$	0.569
Mean Velocity (cm/s)	0.84 (0.48)	1.21 (0.59)	2.84 (1.95)	5.26 (2.77)	9.051	$<0.001^*$	0.492
95 %CEA (cm^2)	0.84 (0.26)	0.87 (0.19)	1.17 (0.35)	1.62 (0.34)	18.221	$<0.001^*$	0.361
RMS AP (cm)	0.26 (0.07)	0.34 (0.12)	0.47 (0.15)	0.61 (0.14)	18.221	$<0.001^*$	0.532
RMS ML (cm)	0.18 (0.09)	0.20 (0.06)	0.31 (0.11)	0.46 (0.15)	21.614	$<0.001^*$	0.575

η^2: small = 0.01, medium = 0.06, large = 0.14 (Cohen 1988).

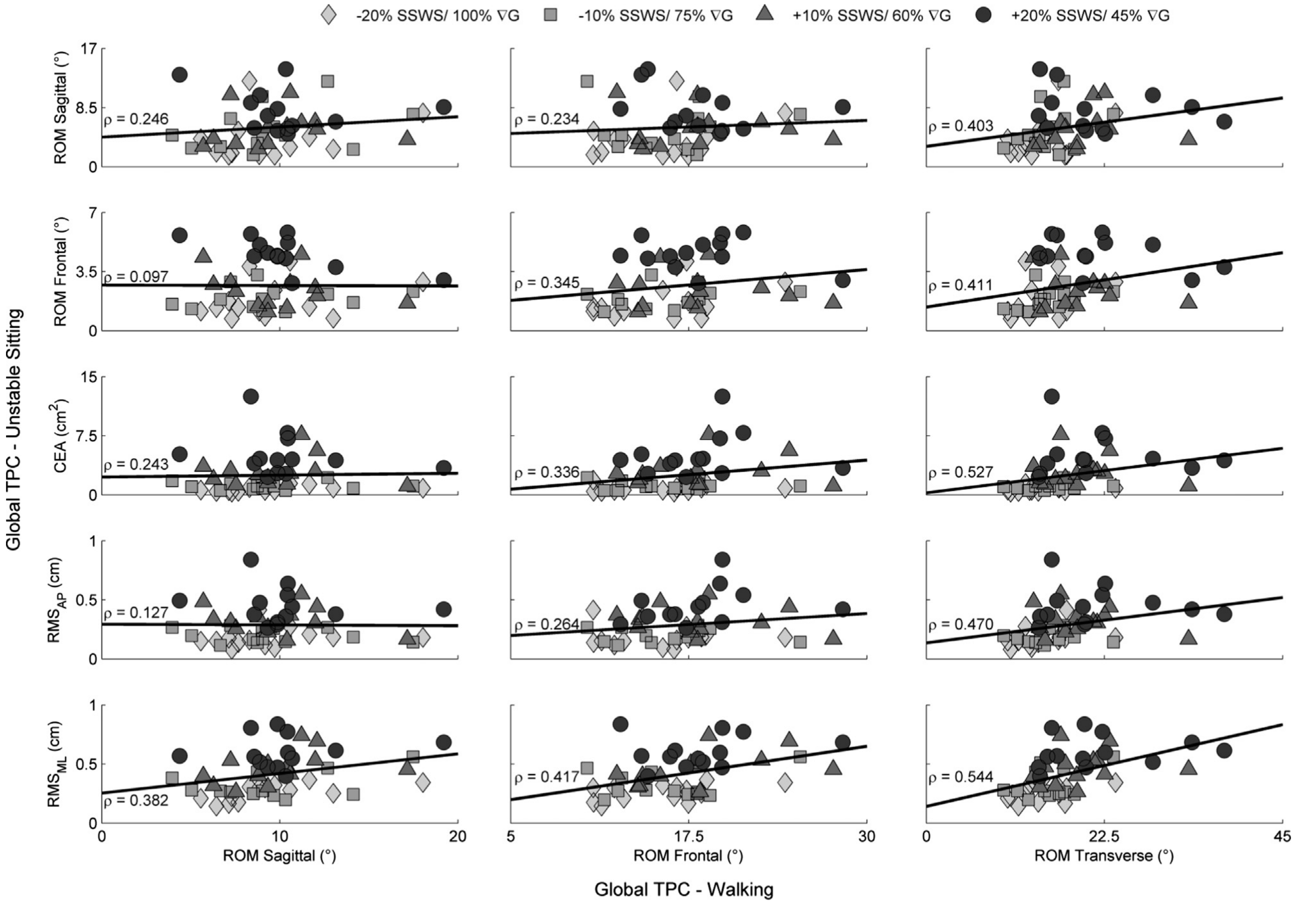

Fig. 1. Trunk-pelvic ranges of motion (ROM), 95% confidence ellipse area (CEA), and RMS positions for unstable sitting plotted against trunk-pelvic ROM while walking. Linear fits and corresponding correlation coefficients (ρ) are displayed. (SSWS = self-selected walking speed; ∇G = gravitational gradient, AP = anteroposterior, ML = mediolateral).

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 λ_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 λ_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.

Acknowledgements

This work was supported, in part, by the Center for Rehabilitation Sciences Research of the Uniformed Services University of the Health Sciences (Award HU0001-15-2-003), Office of the Assistant Secretary of Defense for Health Affairs, via the Peer Reviewed

Orthopaedic Research Program (Award W81XWH-14-2-0144), and the DoD-VA Extremity Trauma and Amputation Center of Excellence (Public Law 110-417, National Defense Authorization Act 2009). The views expressed herein are those of the authors, and do not necessarily reflect the official policy or position of the Department of Defense or U.S. Government.

Conflict of Interest

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

References

Asgari, M., Sanjari, M.A., Mokhtarinia, H.R., Moeini Sedeh, S., Khalaf, K., Parnianpour, M., 2015. The effects of movement speed on kinematic variability and dynamic stability of the trunk in healthy individuals and low back pain patients. Clin Biomech (Bristol, Avon) 30 (7), 682–688. https://doi.org/10.1016/j.clinbiomech.2015.05.005.

Carpes, F.P., Reinehr, F.B., Mota, C.B., 2008. Effects of a program for trunk strength and stability on pain, low back and pelvis kinematics, and body balance: a pilot study. J. Bodyw. Mov. Ther. 12 (1), 22–30. https://doi.org/10.1016/j.jbmt.2007.05.001.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences. Erlbaum Associates, Hillsdale, NJ.

Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R., Sternad, D., 2001. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. J. Biomech. Eng. 123 (1), 27. https://doi.org/10.1115/1.1336798.

Dingwell, J.B., Marin, L.C., 2006. Kinematic variability and local dynamic stability of upper body motions when walking at different speeds. J. Biomech. 39 (3), 444–452. https://doi.org/10.1016/j.jbiomech.2004.12.014.

Grimbergen, Y.A.M., Knol, M.J., Bloem, B.R., Kremer, B.P.H., Roos, R.A.C., Munneke, M., 2008. Falls and gait disturbances in Huntington's disease. Mov. Disord. 23 (7), 970–976. https://doi.org/10.1002/mds.22003.

Hendershot, B.D., Nussbaum, M.A., 2013. Persons with lower-limb amputation have impaired trunk postural control while maintaining seated balance. Gait Posture. 38, 438–442.

Jung, K.S., Cho, H.Y., In, T.S., 2016. Trunk exercises performed on an unstable surface improve trunk muscle activation, postural control, and gait speed in patients with stroke. J Phys Ther Sci 28, 940–944.

Kang, H.G., Dingwell, J.B., 2006. A direct comparison of local dynamic stability during unperturbed standing and walking. Exp. Brain Res. 172 (1), 35–48. https://doi.org/10.1007/s00221-005-0224-6.

Karthikbabu, S., Nayak, A., Vijayakumar, K., Mirsi, Z.K., Suresh, B.V., Ganesan, S., Joshuan, A.M., 2011. Comparison of physio ball and plinth trunk exercise regimens on trunk control and functional balance in patients with acute stroke: a pilot randomized controlled trial. Clinical Rehabilitation 25 (8), 709–719.

Lamoth, C.J., Ainsworth, E., Polomski, W., Houdijk, H., 2010. Variability and stability analysis of walking of transfemoral amputees. Med. Eng. Phys. 32 (9), 1009–1014. https://doi.org/10.1016/j.medengphy.2010.07.001.

Lamoth, C.J., Daffertshofer, A., Meijer, O.G., Beek, P.J., 2006. How do persons with chronic low back pain speed up and slow down? Trunk-pelvis coordination and lumbar erector spinae activity during gait. Gait Posture 23 (2), 230–239. https://doi.org/10.1016/j.gaitpost.2005.02.006.

Larivière, C., Gagnon, D.H., Mecheri, H., 2015. Trunk postural control in unstable sitting: Effect of sex and low back pain status. Clin. Biomech. (Bristol, Avon) 30 (9), 933–939. https://doi.org/10.1016/j.clinbiomech.2015.07.006.

O'Sullivan, P.B., Phyty, G.D.M., Twomey, L.T., Allison, G.T., 1997. Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. Spine 22 (24), 2959–2967.

Portney, L.G., Watkins, M.P., 2009. Foundations of Clinical Research: Application to Practice. Pearson, Upper Saddle River, NJ.

Prieto, T.E., Myklebust, J.B., Hoffmann, R.G., Lovett, E.G., Myklebust, B.M., 1996. Measures of postural steadiness: differences between healthy young and elderly adults. IEEE Transact. Biomed. Eng. 43 (9), 956–966.

Radebold, A., Cholewicki, J., Polzhofer, G.K., Greene, H.S., 2001. Impaired Postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. Spine 26 (7), 724–730.

Richman, J.S., Moorman, R.J., 2000. Physiological time-series analysis using approximate entropy and sample entropy. Am. J. Physiol. Heart Circ. Physiol 278, H2039–H2049.

Rosenstein, M.T., Collins, J.J., De Luca, C.J., 1993. A practical method for calculating largest Lyapunov exponents from small data sets. Physica D 65, 117–134.

Slota, G.P., Granata, K.P., Madigan, M.L., 2008. Effects of seated whole-body vibration on postural control of the trunk during unstable seated balance. Clin .Biomech. (Bristol, Avon) 23 (4), 381–386.

Tinetti, M.E., Speechley, M., Ginter, S.F., 1988. Risk factors for falls among elderly persons living in the community. New England J. Med. 319 (26), 1701–1707.

Van Daele, U., Huyvaert, S., Hagman, F., Duquet, W., Van Gheluwe, B., Vaes, P., 2007. Reproducibility of postural control measurement during unstable sitting in low back pain patients. BMC Musculoskelet Disord 8 (44), 1471–2474.

Van Daele, U., Hagman, F., Truijen, S., Vorlat, P., Van Gheluwe, B., Vaes, P., 2009. Differences in balance strategies between nonspecific and chronic low back pain patients and healthy control subjects during unstable sitting. Spine 34 (11), 1233–1238.

Van Dieen, J.H., Koppes, L.L.J., Twisk, J.W.R., 2010. Postural sway parameters in seated balanceing; their reliability and relationship with balance performance. Gait Posture 31, 42–46.

Van Emmerik, R.E., McDermott, W.J., Haddad, J.M., Van Wegen, E.E., 2005. Age-related changes in upper body adaptation to walking speed in human locomotion. Gait Posture 22 (3), 233–239. https://doi.org/10.1016/j.gaitpost.2004.09.006.

Verheyden, G., Vereeck, L., Truijen, S., Troch, M., Herregodts, I., De Lafosse, C., Weerdt, W., 2006. Trunk performance after stroke and the relationship with balance, gait, and functional ability. Clin. Rehabilitation 20, 451–458.

Yentes, J.M., Hunt, N., Schmid, K.K., Kaipust, J.P., McGrath, D., Stergiou, N., 2013. The appropriate use of approximate entropy and sample entropy with short data sets. Annal. Biomed. Eng. 41 (2), 349–365.

Zazulak, B.T., Hewett, T.E., Reeves, N.P., Goldberg, B., Cholewicki, J., 2007. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. Am. J. Sports Med. 35 (7), 1123–1130. https://doi.org/10.1177/0363546507301585.

Zeni Jr., J.A., Higginson, J.S., 2010. Gait parameters and stride-to-stride variability during familiarization to walking on a split-belt treadmill. Clin. Biomech. (Bristol, Avon) 25 (4), 383–386. https://doi.org/10.1016/j.clinbiomech.2009.11.002.