

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Original Research

Title: Responses of the trunk to multidirectional perturbations during unsupported sitting

Authors: Thrasher, T. Adam¹, Sin, Vivian W.^{2,3}, Masani, Kei^{2,3}, Vette, Albert H.^{2,3}, Craven, B. Cathy³, and Popovic, Milos R.^{2,3}

Institutions: ¹ University of Houston, Department of Health and Human Performance, Houston, TX

² University of Toronto, Institute of Biomaterials and Biomedical Engineering, Toronto, Canada

³ Toronto Rehabilitation Institute, Toronto, Canada

Document version 2.0

30 Jan 2009

Correspondence to:

Adam Thrasher Ph.D.
University of Houston
3855 Holman Street
Garrison Room 104
Houston, TX 77204-6015

Tel: 713-743-5276
FAX: 713-743-9860
E-mail: athrasher3@uh.edu

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Abstract

Understanding how the human body responds to unexpected force perturbations during quiet sitting is important to the science of motor behavior and the design of neuroprostheses for sitting posture. In this study, the performance characteristics of the neck and trunk in healthy individuals were assessed by measuring the kinematic responses to sudden, unexpected force perturbations applied to the thorax. Perturbations were applied in eight horizontal directions. It was hypothesized that displacement of the trunk, settling time and steady-state error would increase when the perturbation direction was diagonal (i.e., anterior-lateral or posterior-lateral) due to the increased complexity of asymmetrical muscle responses. Perturbation forces were applied manually. The neck and trunk responded in a synchronized manner in which all joints achieved peak displacement simultaneously then returned directly to equilibrium. Displacement in the direction of perturbation and perpendicular to the direction of perturbation were both significantly greater in response to diagonal perturbations ($p < 0.001$). The center of mass returned to equilibrium in 3.64 ± 1.42 s after the onset of perturbation. Our results suggest that the trunk sometimes behaves like an underdamped oscillator and is not controlled by simple stiffness. The results of this study are intended to be used to develop a neuroprosthesis for artificial control of trunk stability in individuals with spinal cord injury. [214 words]

Keywords: Sitting stability, trunk stiffness, force perturbation, kinematic response.

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Introduction

During unsupported sitting (i.e., without a backrest), the human trunk performs a complex control task in which the muscles of the trunk are contracted in a coordinated manner to maintain an erect posture and resist external perturbations. The intrinsic mechanics of the lumbar spine and its ligaments are insufficient to support vertical loads greater than 88N (Crisco, Panjabi, Yamamoto, & Oxland, 1992), therefore the muscles spanning the lumbar vertebrae must contract to support the upper body mass. These contractions are modulated by a combination of feedforward control (tonic contractions, also called stiffness), and feedback control (phasic contractions) in response to external perturbations (Moorhouse & Granata, 2006). The natural control mechanism is considered highly efficient, as it allows for quick, yielding movements in response to perturbations, and a smooth, controlled return to equilibrium.

Neuromuscular disorders that affect the trunk musculature, such as Spinal Cord Injury (SCI) and Parkinson's Disease (PD), typically result in postural instability (Bjerkefors, Carpenter, & Thorstensson, 2007; Chen et al., 2003; Horak, Dimitrova, & Nutt, 2005; Kamper, Barin, Parnianpour, Reger, & Weed, 1999). In a survey of individuals with paraplegia, trunk stability was identified as the third most important gain that would dramatically improve their quality of life (Anderson, 2004). Functional Electrical Stimulation (FES) is being explored as a potential technique to activate the paralyzed trunk musculature during sitting in a way that improves stability and allows individuals with SCI to carry out bimanual tasks, which they otherwise are unable to perform (Kukke & Triolo, 2004; Wilkenfeld, Audu, & Triolo, 2006). Current FES

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

systems for enhancing sitting stability are experimental and use simple open-loop stimulation of the muscles to stiffen the trunk (akin to anticipatory tonus). These FES systems do not provide reactive responses to perturbations. That is, they are unable to compensate for external perturbations to the torso during FES-assisted sitting. Our primary objective is to develop an FES system that will be able to improve sitting stability in individuals with SCI by providing real-time control over both tonic and phasic muscles contractions in response to individuals sitting posture and external perturbations. The secondary objective is to develop this system such that it mimics sitting dynamics of healthy individuals. The present study is the first step in that process, which is to analyze the dynamic performance of healthy humans during sitting as a basis upon which to design the proposed FES system. Particularly, we are interested in the performance characteristics of the healthy trunk in response to external force perturbations that are applied in different horizontal directions.

External force perturbations have been used in many postural control studies to gain insights into the motor control and stability performance of the trunk (Gardner-Morse & Stokes, 2001; Rietdyk, Patla, Winter, Ishac, & Little, 1999; Stokes, Fox, & Henry, 2006). Kinematic and neuromuscular responses to perturbation have revealed many characteristics of the control mechanisms of the trunk. Several studies have observed that the trunk response varies with respect to the direction of perturbation (Gardner-Morse & Stokes, 2001; Horak et al., 2005; Preuss & Fung, 2007). This is in part due to the anatomical arrangement of the trunk musculature. The spinal column, which is located in the posterior of the trunk, acts as a fulcrum for flexion and extension, and it is flexed and extended by the rectus abdominus and erector spinae muscles, respectively.

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

The rectus abdominus muscles have a long moment arm as compared to their antagonists, the erector spinae muscles. Whereas the abdominal oblique muscles, which provide lateral stabilizing forces, are arranged symmetrically.

In the present study, we set out to describe the performance characteristics of the stable trunk in response to unexpected impulse perturbations. We hypothesized that diagonal perturbations, applied in the horizontal plane at a 45° angle to the medial-lateral axis, would result in a less effective response as compared to perturbations in the purely anterior-posterior or lateral directions, due to the increased complexity of an asymmetrical muscular response. Our analysis focuses on characteristics of the COM displacement in response to an impulse perturbation applied to the thorax, and the dissipation of kinetic energy as the body returns to equilibrium. Peak COM displacement during perturbation is often used as an indicator of postural stability (Bjerkefors et al., 2007; Horak et al., 2005). It is presumed that a smaller COM displacement is representative of a more stable system. We also analyzed other standard performance characteristics such as overshoot, settling time and steady-state error.

Methods

Subjects

Thirteen healthy male adults (Age: 21 to 43 years; Height: 177.0 ± 4.7 cm; Weight: 70.5 ± 9.6 kg) participated in this study. They had no history of neurological disorders or spinal deformity. All participants were right-handed and gave informed consent to participate in the study after receiving a detailed explanation about the purposes, benefits,

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

and risks associated with the participation in the study. The experimental protocol used in this study was approved by the institutional ethics committee.

Apparatus

Each subject was seated on a tall wooden box such that the vertical face of the box was in contact with the calves (see Figure 1). There was no back support and no feet support. The feet hung freely and did not contact the floor. There was light contact between the subject's heels and the vertical surface of the box. This was done on purpose to minimize the contribution of the legs and feet in the control of sitting. No cushions were used. The top surface of the box was a rigid metal plate. The subject wore a tight-fitting t-shirt and a special harness around the thorax. Eight cables were attached to different points on the harness via carabineers. Each cable was used to apply a horizontal force perturbation in one of the following directions, relative to the sagittal axis: 0° (anterior), 45°, 90° (right), 135°, 180° (posterior), 225°, 270° (left), 315°.

External force perturbations were applied to the cables manually by an experimenter holding one of the cables in series with a force transducer (sensor: MLP-100-CO-C, Transducer Techniques, USA; and amplifier: Model 9243, Burster, Germany). The force transducer had a range of 444.8 N. The experimenter applied a force impulse by quickly tugging on the cable in a practiced manner. The same experimenter applied perturbations in all the trials. All force transducer signals were collected at a sampling frequency of 2,000 Hz using a 12-bit analog-to-digital converter (NI 6071E, National Instrument, USA) and custom data acquisition software.

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Kinematic data was recorded using an Optotrak 3020 motion analysis system (Northern Digital Inc., Canada). The 3-dimensional position of 19 markers attached to the subject's trunk and head were recorded at 100 Hz. The marker set used was designed specifically for this experiment. It consisted of three markers located on the spinous processes of C6, T9 and L3. Three sets of four markers were mounted on rigid plates which were attached to the back of the subject's head, thorax and abdomen. Four additional markers were placed on the anterior sacral iliac spines.

Protocol

The subjects were instructed to cross their arms lightly, close their eyes, and sit in a relaxed and natural posture. A total of 40 perturbation trials (8 directions, 5 trials each) were applied to the subjects. The order of the perturbation directions was randomly determined, such that the subjects were not pulled in the same direction consecutively to prevent anticipation, which has been shown to have a significant effect on the perturbation response (Gilles, Wing, & Kirker, 1999). The subject wore a headphone and listened to whale music and nature sounds found in national parks. During the perturbation trials, two researchers would be holding the ropes in two different directions. One direction was the intended pulling direction, where the force transducer was attached. The purpose of the other direction was to prevent subject from anticipating the pulling direction. To maintain consistency, all external perturbations were pulled by one researcher. Subjects were informed that breaks would be given after every 10 trials.

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Analysis

A 3-dimensional, 6 degree-of-freedom model of a seated human was developed. The model was an inverted, compound pendulum consisting of three segments: (1) the neck and head, (2) the arms and thorax, and (3) the abdomen. The pelvis and legs were assumed to be static with respect to the inertial frame of reference, and did not move significantly during the experiments. The joints of the model were located at the C6, T9 and L3 vertebrae and were defined respectively as the neck, the thoraco-lumbar joint and the lumbo-sacral joint. The individual joints had two degrees of freedom, allowing flexion/extension as well as lateral flexion. The 3-dimensional orientation of each segment was determined by an array of four optical markers mounted on a rigid plate, which was attached to the subject's back.

The inertial properties of the three body segments were approximated using the regression methods described by Zatsiorsky et al., which are based on total body mass and height (Zatsiorsky, Seluyanov, & Chugunova, 1990). The position of each segmental COM was assumed to be in the geometrical center of the segment, which was estimated using standard anthropometric data (Winter, 1990). Lateral symmetry was assumed.

The following performance variables were determined: (1) The total kinetic energy of the 3-segment model, (2) The peak displacement of the upper body COM in the direction of perturbation, D_x ; (3) The peak displacement of the upper body COM in the horizontal direction perpendicular to the direction of perturbation, D_y ; (4) D_x normalized with respect to the perturbation impulse – this was done to account for variations in the manually applied perturbation force; (5) D_y normalized with respect to the perturbation impulse; (6) Steady-state error between the initial and final COM displacement; and (7)

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

The settling time, T_s , required for the COM displacement to settle within 5% of the final displacement for at least 2 seconds. A typical displacement response is shown in Figure 2. The onset of perturbation was determined as the instant when the cable force exceeded 5% of its peak value for each trial. Kinetic energy was normalized with respect to the total mechanical work done by the perturbation, as calculated by load cell measurement and the displacement of the centroid of the four thorax markers in the direction of perturbation.

Some trials produced overshoot, which was defined as displacement beyond the final resting position of at least 5% of the peak displacement value. The cases involving overshoot were counted. Vertical displacement of the COM was detected, but neglected in our analyses. Optical markers went missing in several trials. In most cases, only one marker of a rigid body set was lost, and the position of the rigid body could be reconstructed using the other three markers. However, in cases where more than one marker went missing for more than 0.1 s, it was impossible to determine the COM. Thus, 18 trials out of the 520 recorded were discarded because of missing markers.

The displacement response was tested with respect to the six performance variables to determine if there was an effect due to perturbation direction or trial order. Hypothesis tests were performed using repeated measures ANOVA with two within-subjects factors (trials and direction of perturbation). Separate ANOVA models were analyzed for each dependent variable. We interpreted the ANOVA results using the Huynh-Feldt adjustment for violation of the sphericity assumption. The level of significance was set at $p \leq 0.05$.

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Results

The basic kinematic response to perturbations was consistent between all subjects. The neck and thoraco-lumbar joints both flexed/extended in a direction opposite to the external force, while the lumbo-sacral joint flexed in the direction of the force. Figure 3 shows the individual joint ranges of motion for all subjects, trials and perturbation directions combined.

During the response to perturbation, the three joints of the model flexed in unison reaching their maximum displacements at approximately the same time. This can be seen in the kinetic energy of the response, shown in Figure 4. The kinetic energy reached a peak value of $35 \pm 12\%$ of the work done by the perturbation, and then quickly returned to almost zero value, indicating that the body is instantaneously at rest. The kinetic energy then peaked a second time at a much lower value ($4.2 \pm 0.9\%$ of the work done by the perturbation), indicating a significant dissipation of energy, before returning to equilibrium.

The total upper body COM trajectories for a typical subject are shown in Figure 2B. The COM first tended to displace in the direction of perturbation. Then it sometimes displaced perpendicular to the perturbation resulting in a separate return path. The peak displacement of the COM for all subjects and all trials was 127 ± 42 mm in the direction of perturbation, and 22.6 ± 15.8 mm perpendicular to the direction of perturbation. When normalized with respect to impulse, these values become 3.27 ± 1.11 mm/Ns (parallel) and 0.49 ± 0.32 mm/Ns (perpendicular). Both normalized components of displacement were significantly greater in response to diagonal perturbations compared to perturbations in the orthogonal directions (i.e., anterior,

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

posterior and lateral) ($p < 0.001$). The settling time was measured to be 3.64 ± 1.42 s, and it did not vary significantly with respect to perturbation direction ($p = 0.543$). The steady-state error, which is the difference between the initial equilibrium position and the final equilibrium position, was 9.96 ± 8.75 mm, and it did not vary with respect to perturbation direction ($p = 0.330$). These results are summarized in Figure 5. The displacement response involved overshoot in 105 of the 352 trials analyzed.

The manual perturbation force varied between 92.2 and 293.0 N, with an average value of 186.6 N and a standard deviation of 35.3 N. The perturbation force was found to vary significantly between subjects ($p < 0.001$) and also with respect to perturbation direction ($p < 0.001$). There was no significant effect of trial order on the perturbation force, perturbation impulse or any of the performance variables measured.

Discussion

Sitting is an activity that most of us perform every day, and we do it more than any other activity during the day. In certain environments, such as on a train, a bus, or in a wheelchair, unexpected perturbations occur frequently in the form of external forces (bumps and pushes), or movements of the sitting surface. In this study, we set out to evaluate the kinematic responses to perturbations during sitting, because normative data for this common event are not well documented. As we wish to design a neuroprosthesis for sitting for people with spinal cord injury, the normal response characteristics to perturbations during sitting are essential for comparing and evaluating the performance of a neuroprosthetic system.

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Our analysis of the kinetic energy of the perturbation responses revealed that an average of 35% of the work done by the perturbation was translated into kinetic energy. This indicates an effective damping mechanism. The three joints of our head and trunk model acted in a synchronized manner, reaching a state of instantaneous rest. This was confirmed by a near zero value of kinetic energy after the initial response. The body was then returned to equilibrium slowly, the entire response lasting an average of 3.64 s.

Based on the biomechanical and musculoskeletal features of the trunk, we hypothesized that the trunk would perform in a more stable manner in response to perturbations in the anterior-posterior or lateral directions. This hypothesis was confirmed by our observation that perturbation direction had a measurable effect on postural stability. This was seen in terms of the peak COM displacement (normalized with respect to perturbation impulse). There was less COM displacement when perturbations were applied orthogonally. This indicates that the trunk is more stable in the purely orthogonal directions. Most of studies that used multi-directional perturbations for standing posture focused on the comparison of body reactions between in anterior-posterior and lateral directions (Allum, Carpenter, & Honegger, 2003). In standing posture, the body reactions are different, since the dynamics are very different between these two directions, i.e., the ankle joint is dominant in anterior-posterior direction while the hip joint is dominant in lateral direction (Winter, 1990). However, few studies focused on the difference of responses to orthogonal and diagonal directions. Horak et al. (Horak et al., 2005) compared subjects with Parkinson's Disease to healthy age-matched subjects, and concluded that the healthy subjects demonstrated consistent stability measures in all eight directions, which was contrary to the researchers' expectations.

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

A significant amount of COM displacement during perturbed quiet sitting was also seen in the horizontal direction perpendicular to the perturbation. This displacement was larger when diagonal perturbations were applied. It likely occurs due to asymmetries in the posture and muscle loads before and during the response. This result was expected, because there is no anatomical symmetry with respect to diagonal axes in the cross-section of the trunk.

Overshoot was seen in 30% of the trials. Overshoot is a characteristic of many physical systems, including an underdamped oscillator or systems with a secondary closed-loop controller. It is not indicative of ineffective control, unless oscillation continues for many cycles. Since it only occurred in a small number of the trials that we analyzed, it is difficult to make any conclusions about normal trunk control from it.

Our analysis of the steady-state error revealed that trunk control is more complex than simple stiffness. Even though the external force returned quickly to zero, the COM rarely returned to its initial position after the perturbation. The difference between the initial COM displacement and the final COM displacement was 9.96 ± 8.75 mm. A system that operates as a simple stiffness controlled system, such as a spring-loaded inverted pendulum, would return to its initial position after the perturbation.

Interestingly, we found no direction effect in terms of the settling time or steady-state error in the COM displacement response. Even though the diagonal perturbations were characterized by larger COM displacements, the COM was returned to a resting position in a similar amount of time and a similar distance from the initial position. This may indicate that the temporal parameters of the reflex mechanisms act to improve upon

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

a simple stiffness response and return the trunk to an equilibrium position by increasing transient muscle forces.

The manually applied perturbation force was not consistent in this experiment. It had a high variability and range. We found that the perturbation force varied significantly between subjects and with respect to direction (diagonal perturbations tended to be stronger).

The results of this study reveal some important control mechanisms associated with trunk stability in able-bodied individuals, particularly the effective manner in which kinetic energy is dissipated. Ultimately, these results will be used to develop a neuroprosthesis for artificial control of trunk stability. The results of this study will be used as a baseline against which the performance of a neuroprosthesis for sitting will be measured.

Conclusions

This study reveals some relevant characteristics of the control mechanisms of quiet sitting. First, we discovered that the joints of the upper body displace in a simultaneous manner reaching an instantaneous rest position (zero kinetic energy) before returning to equilibrium. However, subjects seldom returned to the initial equilibrium position. Instead, the COM assumed a slightly different equilibrium position. This is an indication that the control mechanism used to maintain sitting posture does not operate as a simple stiffness controller. We also discovered that the COM displacement in response to perturbation tends to be more pronounced if the perturbation is applied diagonally as compared to perturbations along the sagittal or transverse axes. We observed that

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

direction of perturbation did not influence the settling time or new steady-state position of the COM.

Acknowledgements

This study was supported by grants from Canadian Institute of Health Research (#129179), Natural Sciences and Engineering Research Council of Canada (#249669), Ministry of Health and Long Term Care in Ontario, Canadian Paraplegic Association Canada, and Toronto Rehabilitation Institute.

Original research article for submission to *Journal of Applied Biomechanics* in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

References

- Allum, J. H., Carpenter, M. G., & Honegger, F. (2003). Directional aspects of balance corrections in man. *IEEE Eng Med Biol Mag*, 22(2), 37-47.
- Anderson, K. D. (2004). Targeting recovery: priorities of the spinal cord-injured population. *J Neurotrauma*, 21(10), 1371-1383.
- Bjerkefors, A., Carpenter, M. G., & Thorstensson, A. (2007). Dynamic trunk stability is improved in paraplegics following kayak ergometer training. *Scand J Med Sci Sports*.
- Chen, C. L., Yeung, K. T., Bih, L. I., Wang, C. H., Chen, M. I., & Chien, J. C. (2003). The relationship between sitting stability and functional performance in patients with paraplegia. *Arch Phys Med Rehabil*, 84(9), 1276-1281.
- Crisco, J. J., Panjabi, M. M., Yamamoto, I., & Oxland, T. R. (1992). Euler stability of the human ligamentous lumbar spine: Part II Experiment. *Clin Biomech (Bristol, Avon)*, 7, 19-26.
- Gardner-Morse, M. G., & Stokes, I. A. (2001). Trunk stiffness increases with steady-state effort. *J Biomech*, 34(4), 457-463.
- Gilles, M., Wing, A. M., & Kirker, S. G. (1999). Lateral balance organisation in human stance in response to a random or predictable perturbation. *Exp Brain Res*, 124(2), 137-144.
- Horak, F. B., Dimitrova, D., & Nutt, J. G. (2005). Direction-specific postural instability in subjects with Parkinson's disease. *Exp Neurol*, 193(2), 504-521.

Original research article for submission to *Journal of Applied Biomechanics* in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

- Kamper, D., Barin, K., Parnianpour, M., Reger, S., & Weed, H. (1999). Preliminary investigation of the lateral postural stability of spinal cord-injured individuals subjected to dynamic perturbations. *Spinal Cord*, 37(1), 40-46.
- Kukke, S. N., & Triolo, R. J. (2004). The effects of trunk stimulation on bimanual seated workspace. *IEEE Trans Neural Syst Rehabil Eng*, 12(2), 177-185.
- Moorhouse, K. M., & Granata, K. P. (2006). Role of reflex dynamics in spinal stability: Intrinsic muscle stiffness alone is insufficient for stability. *J Biomech*.
- Preuss, R., & Fung, J. (2007). Musculature and biomechanics of the trunk in the maintenance of upright posture. *J Electromyogr Kinesiol*.
- Rietdyk, S., Patla, A. E., Winter, D. A., Ishac, M. G., & Little, C. E. (1999). NACOB presentation CSB New Investigator Award. Balance recovery from medio-lateral perturbations of the upper body during standing. North American Congress on Biomechanics. *J Biomech*, 32(11), 1149-1158.
- Stokes, I. A., Fox, J. R., & Henry, S. M. (2006). Trunk muscular activation patterns and responses to transient force perturbation in persons with self-reported low back pain. *Eur Spine J*, 15(5), 658-667.
- Wilkenfeld, A. J., Audu, M. L., & Triolo, R. J. (2006). Feasibility of functional electrical stimulation for control of seated posture after spinal cord injury: A simulation study. *J Rehabil Res Dev*, 43(2), 139-152.
- Winter, D. A. (1990). *Biomechanics and Motor Control of Human Movement* (3rd ed.). New York: John Wiley & Sons.
- Zatsiorsky, V. M., Seluyanov, V. N., & Chugunova, L. G. (1990). Methods of determining mass-inertial characteristics of human body segments. In

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Contemporary problems in biomechanics (pp. 272-291). Massachusetts: CRC

Press.

For Peer Review

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

Figure Captions

- Figure 1: Illustration of subject sitting on experimental apparatus. Horizontal force perturbations were applied through one of eight cables attached to a harness worn about the chest.
- Figure 2: (A) COM displacement in the transverse plane from all 40 trials (5 in each direction) of subject 1 overlaid. (B) A typical COM displacement response, from which performance variables were identified.
- Figure 3: Range of motion of the segmental joints of all subjects in response to perturbation. Bars indicate mean values. Error bars represent one standard deviation. Negative values indicate joint motion away from the perturbation, e.g. the neck flexes in response to forward forces and extends in response to backward forces.
- Figure 4: Kinetic energy response to perturbation (representative sample) normalized with respect to total mechanical work done by perturbation. Time zero indicates the onset of perturbation.
- Figure 5: Comparisons between upper body COM responses to perturbations in the orthogonal direction and perturbations in diagonal directions in terms of the six performance variables. (A) displacement parallel to perturbation force, (B)

Original research article for submission to Journal of Applied Biomechanics in Feb 2009

Responses of the trunk to multidirectional perturbations during unsupported sitting

Thrasher TA, Sin V, Masani K, Vette A, Craven BC, Popovic MR

normalized displacement parallel to perturbation force, (C) displacement

perpendicular to perturbation force, (D) normalized displacement

perpendicular to perturbation force, (E) settling time, (F) steady-state error.

For Peer Review

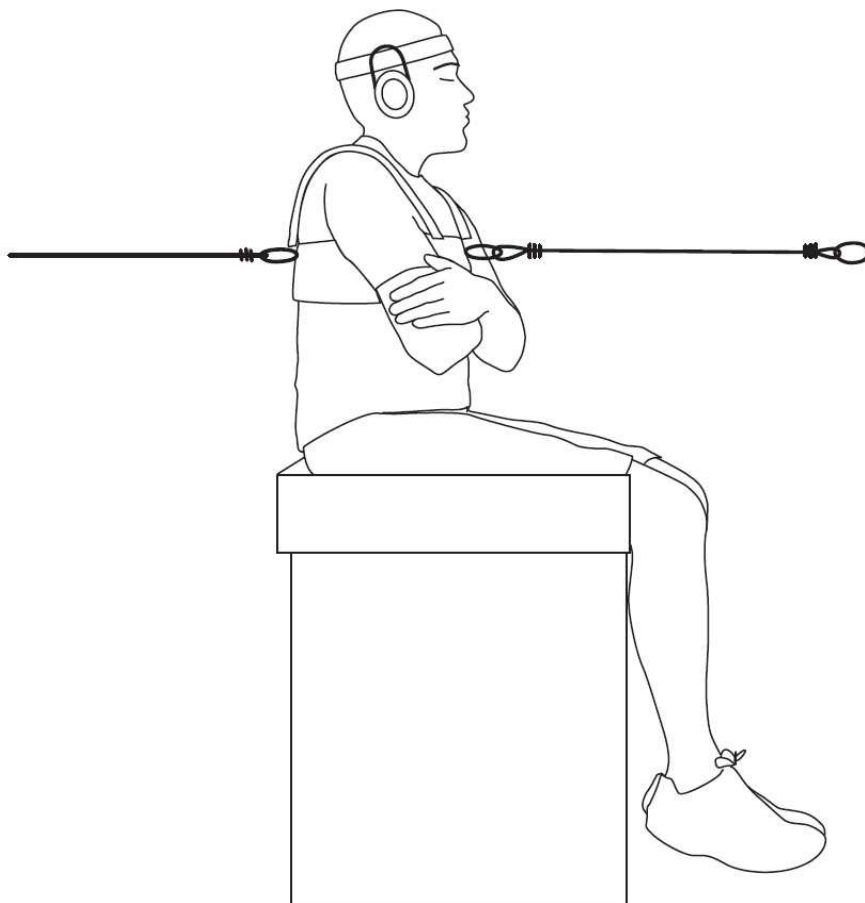
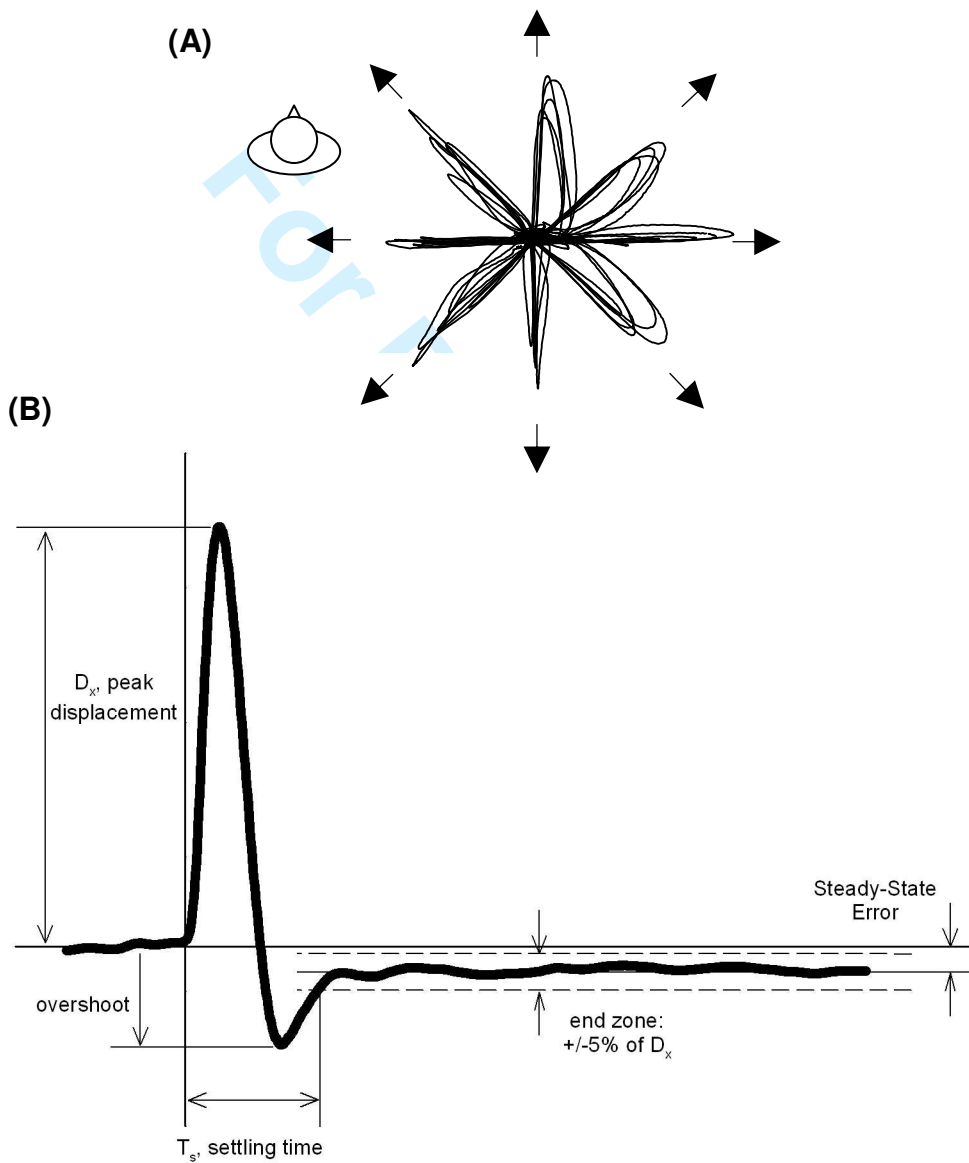
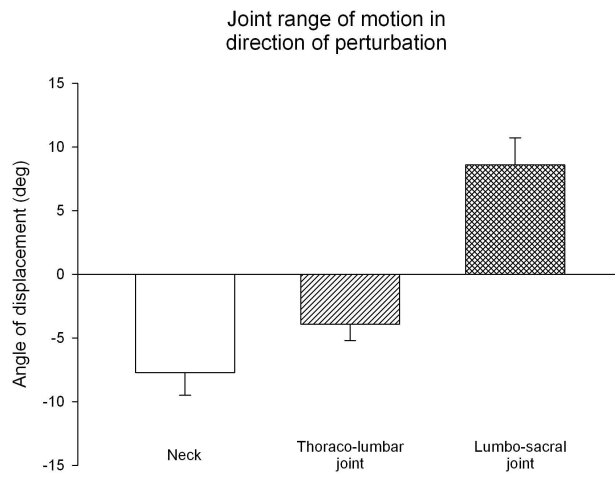


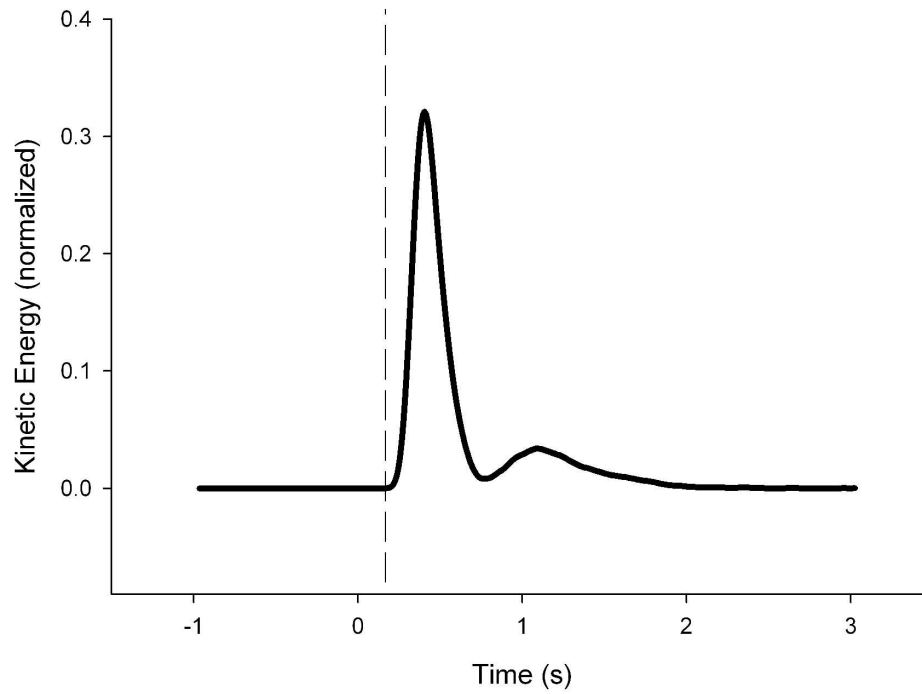
Illustration of subject sitting on experimental apparatus. Horizontal force perturbations were applied through one of eight cables attached to a harness worn about the chest.
330x308mm (72 x 72 DPI)



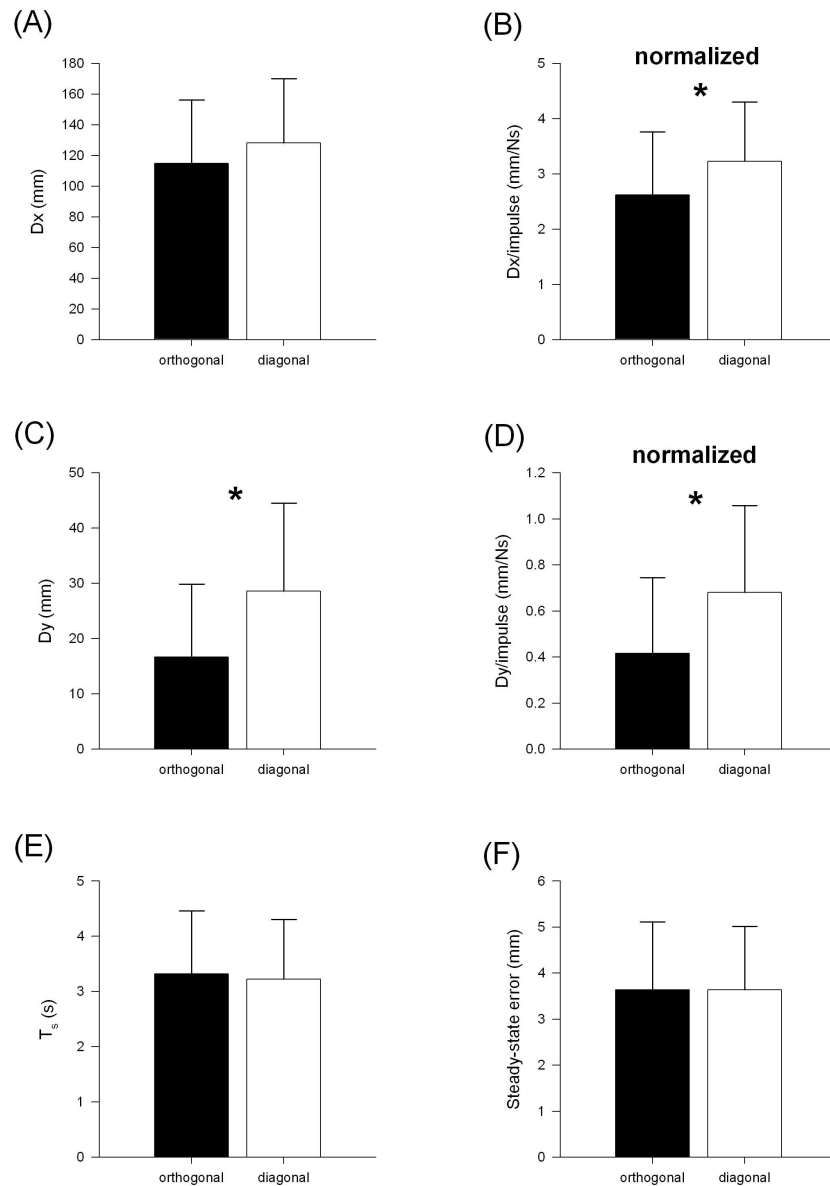




Range of motion of the segmental joints of all subjects in response to perturbation. Bars indicate mean values. Error bars represent one standard deviation. Negative values indicate joint motion away from the perturbation, e.g. the neck flexes in response to forward forces and extends in response to backward forces.
215x279mm (300 x 300 DPI)



Kinetic energy response to perturbation (representative sample) normalized with respect to total mechanical work done by perturbation. Time zero indicates the onset of perturbation.
154x117mm (600 x 600 DPI)



Comparisons between upper body COM responses to perturbations in the orthogonal direction and perturbations in diagonal directions in terms of the six performance variables. (A) displacement parallel to perturbation force, (B) normalized displacement parallel to perturbation force, (C) displacement perpendicular to perturbation force, (D) normalized displacement perpendicular to perturbation force, (E) settling time, (F) steady-state error.

204x248mm (300 x 300 DPI)