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Multidirectional quantification of trunk stiffness and damping during unloaded natural sitting

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ABSTRACT

Trunk instability during sitting is a major problem following neuromuscular injuries such as stroke and spinal cord injury. In order to develop new strategies for alleviating this problem, a better understanding of the intrinsic contributions of the healthy trunk to sitting control is needed. As such, this study set out to propose and validate a novel methodology for determining multidirectional trunk stiffness during sitting using randomized transient perturbations. Fifteen healthy individuals sitting naturally on a custom-made seat were randomly perturbed in eight horizontal directions. Trunk stiffness and damping were quantified using force and trunk kinematics in combination with translational and torsional models of a mass-spring-damper system. The results indicate that stiffness and damping of the healthy trunk are roughly symmetrical between the two body sides. Moreover, both quantities are smallest in the anterior and largest in the lateral directions. In conclusion, a novel protocol for identifying intrinsic trunk stiffness and damping has been developed, eliminating anticipation effects with respect to perturbation timing and direction. Subsequent studies will use these findings as a reference not only for quantifying trunk stiffness and damping in individuals with various neuromuscular disorders, but also for assessing whether neuroprostheses could increase upper body stiffness and, hence, stability.

1. Introduction

Trunk instability is a major problem for people with neuromuscular disorders affecting the transmission and integration of sensorimotor information. It not only compromises their independence during activities of daily living (ADL) [1,2], but can also lead to secondary health complications such as kyphosis, pressure sores, and reduced respiratory capacity [3–5]. Consequently, it is not surprising that, for example, people with spinal cord injury (SCI) prioritize the recovery of trunk stability over the recovery of walking function [6]. Furthermore, trunk stability has recently been identified as the key factor in human balance control and mobility, regardless of the movement or task to be completed. This can be ascribed to the fact that over half of the body's mass is located above the pelvis [7]. As a consequence, the ability to balance the trunk is critical for maintaining stability of the entire body [8] during sitting, standing, walking, and other ADL.

While the topic of trunk stability has enjoyed much attention in the scientific literature, the primary focus has been on inter-vertebral stability (e.g., in the context of low back pain or injury) [9–11], rather than on postural stability. Considering that the human spine is inherently unstable, however, the trunk musculature is pivotal for maintaining the upper body's postural integrity against various environmental challenges related to (1) increased loading (e.g., during object lifting) and (2) transient perturbations (e.g., during a subway/train ride). In particular, the trunk's stability against increased loading is ensured by co-activating the musculature surrounding the spine, resulting in increased multidirectional stiffness [12]. Such an increase in muscle stiffness has additionally been demonstrated to contribute to trunk stabilization against transient lateral perturbations [13–15].

Generally, the muscle stiffness required to complement direction-specific joint (or inter-vertebral) stiffness to overcome postural challenges consists of two components: intrinsic and reflex stiffness. On the one hand, *intrinsic stiffness* is determined by the mechanical properties of the muscle-tendon complex and the pre-activated trunk musculature (open-loop control) [16]. On the other hand, *reflex stiffness* is generated in response to a perturbation via neural reflex pathways (closed-loop control) and is proportional to the angular change at the joint [17–19]. For large

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perturbations, the contribution of reflex stiffness is essential for the maintenance of trunk stability [20]. For gentle perturbations, however, tonic pre-activation of the trunk musculature (i.e., intrinsic stiffness) may already suffice for trunk stability, alleviating the need for further reflex-driven and direction-specific activation of the musculature [14,21].

In the context of trunk stability, the intrinsic stiffness of the spine and trunk musculature can be assessed globally by quantifying the stiffness of the trunk itself. When perturbed by a small force, the trunk has been shown to behave like a mass-spring-damper system [22]. Using this representation, the stiffness of the trunk can be 'reverse-engineered' by measuring externally applied forces and the resulting trunk kinematics (*system identification*). Various studies have estimated trunk stiffness for one or more perturbation directions, and this under loaded and/or unloaded conditions [13,15,22,23]. No study, however, has utilized the *same* experimental procedures and conditions to identify *translational* and *torsional* estimates of trunk stiffness during the natural (unloaded) *sitting* posture for *all* anterior–posterior, lateral, and diagonal directions (total of eight directions). Since trunk stiffness is believed to vary depending on the direction of trunk deflection, such a study may be important for better understanding the contribution of intrinsic trunk stiffness to sitting stability during ADL and for developing neuroprostheses for people with neuromuscular disorders. Based on these considerations, the purpose of this study was to: (1) propose and validate a novel methodology for accurately and efficiently determining multidirectional trunk stiffness during sitting (translational and torsional estimates); and (2) identify a control set of such stiffness values for healthy and young individuals as a benchmark for future studies with different populations, e.g., individuals with SCI or stroke.

2. Methods

2.1. Subjects

Fifteen healthy and young male individuals were invited to participate in this study (age 26.7 ± 4.6 years; height 176 ± 7 cm; weight 72.5 ± 8.1 kg; mean ± standard deviation). All subjects were free from any prior neurological, vestibular, and sensory impairment as well as from any injuries or disorders of the musculoskeletal system. In addition, none of the subjects reported any prior diagnosis of spinal scoliosis or other conditions affecting seated posture. Each subject gave written informed consent to the experimental procedure, which was approved by the local ethics committee in accordance with the declaration of Helsinki on the use of human subjects in experiments.

2.2. Experimental setup and protocol

Each subject's trunk stiffness and damping were identified using a mathematical description of a second-order mass-spring-damper system in combination with force and kinematics data from perturbation experiments. During the testing, the subject sat on a custom-made sitting apparatus without touching the ground with his feet, had the forearms resting on his lap, and maintained an upright posture with eyes closed. One of the subject's hands held an emergency safety button that, when pressed, shut down the power of the device applying the external perturbation forces to the subject.

To generate the postural perturbations, a custom-made perturbation system, known as the *Portable and Automated Postural Perturbation System* (PAPPS) [24], was used. The PAPPS, which consisted of eight identical perturbation units forming an octagonal structure, delivered horizontal perturbations in the following

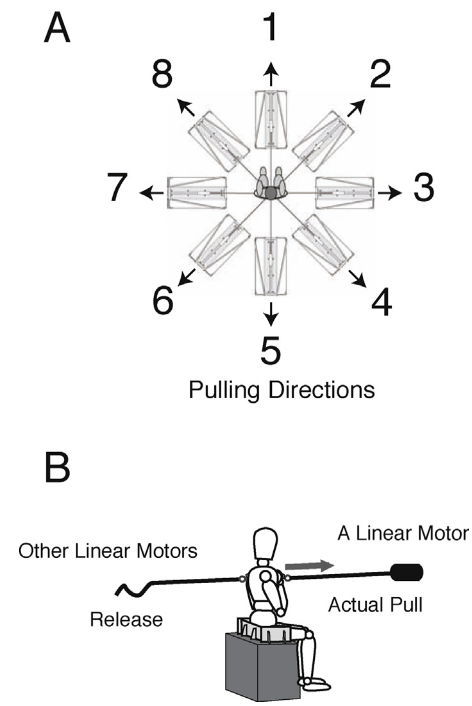

Fig. 1. Schematic of the eight different perturbation directions (A) and the applied perturbation concept (B). The PAPPS delivered horizontal perturbations in the following directions: anterior (1), anterior-right (2), right (3), posterior-right (4), posterior (5), posterior-left (6), left (7), and anterior-left (8). During each trial, a randomly determined PAPPS unit displaced the subject's trunk by 2 cm, while the remaining seven units moved toward the subject to prevent any form of interference with or resistance to the evoked response.

directions (Fig. 1A): anterior (1), anterior-right (2), right (3), posterior-right (4), posterior (5), posterior-left (6), left (7), and anterior-left (8). The core of each perturbation unit consisted of a linear servo motor (TBX2508-D, Rotalec Inc., Quebec, Canada) that was in series with a load cell (SML 300, Interface Inc., AZ, USA) measuring the pulling force. The linear servo motor controlled the position of the load cell, which was connected to the subject via a short stainless steel cable and a belt harness (Fig. 1B). The harness was secured to the subject's trunk over the trunk segment associated with the tenth thoracic vertebra (T10), which has been suggested to represent the behavior of the center of mass (COM) of the trunk [15]. A motion analysis system (Optotrak 3020, NDI Inc., Ontario, Canada) was used to measure body movement during the perturbations. In order to avoid interference with the perturbation harness, two markers were used to capture the location of the T10 vertebra: one was attached 6 cm below and the other one 6 cm above T10 (*see online supplementary data for justification*). Note that the T10 landmark was identified via palpation by two experienced researchers. All recorded signals were collected with a sampling frequency of 500 Hz and low-pass filtered using a fifth order, zero-phase lag Butterworth filter with a cutoff frequency of 10 Hz [7,21].

The entire perturbation protocol lasted about 15–20 min, with 80 randomized pulls in total and 10 pulls in each direction.[1] Halfway through the experimental session, the subject had a two-minute resting period and was asked to relax his trunk. Prior to each pull, all eight cables applied a projected force of 40 N to the subject.

[1] Note that these 80 'natural' trials alternated with 80 'supported' trials during which constant, low-level functional electrical stimulation (FES) was applied to the abdominal and lower erector spinae muscles. Respective FES-supported results are not subject of the present report.