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A Trunk Support System to Identify Posture Control Mechanisms in Populations Lacking Independent Sitting

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Abstract

Populations with moderate-to-severe motor control impairments often exhibit degraded trunk control and/or lack the ability to sit unassisted. These populations need more research, yet their underdeveloped trunk control complicates identification of neural mechanisms behind their movements. The purpose of this study was to overcome this barrier by developing the first multi-articulated trunk support system to identify visual, vestibular, and proprioception contributions to posture in populations lacking independent sitting. The system provided external stability at a user-specific level on the trunk, so that body segments above the level of support required active posture control. The system included a tilting surface (controlled via servomotor) as a stimulus to investigate sensory contributions to postural responses. Frequency response and coherence functions between the surface tilt and trunk support were used to characterize system dynamics and indicated that surface tilts were accurately transmitted up to 5Hz. Feasibility of collecting kinematic data in participants lacking independent sitting was demonstrated in two populations: two typically developing infants, ~2-8 months, in a longitudinal study (8 sessions each) and four children with moderate-to-severe cerebral palsy (GMFCS III-V). Adaptability in the system was assessed by testing 16 adults (ages 18-63). Kinematic responses to continuous pseudorandom surface tilts were evaluated across 0.046–2Hz and qualitative feedback indicated that the trunk support and stimulus were comfortable for all subjects. Concepts underlying the system enable both research for, and rehabilitation in, populations lacking independent sitting.

Keywords

Posture control; trunk support; sitting; cerebral palsy; infant

I. Introduction

Populations with moderate-to-severe motor control impairments often exhibit degraded trunk control and/or lack the ability to sit unassisted. For example, over 30% of children with cerebral palsy (CP) never achieve stable sitting[1]. Similarly, poor trunk control is common in spinal cord injury[2], cerebrovascular accident[3] and multiple sclerosis[4]. Populations lacking independent sitting require more financial commitments for assistive devices, care-givers, have increased frequency of secondary complications due to decreased activity levels, and have poor prognosis compared to those with less severe disabilities[5]. Yet these severely impaired populations receive the least amount of motor control research[6,7]. Previous research approaches include using a reclined seat[8-10] or arms as a base of support[11], both of which reduce the need for active posture control in the trunk. Therefore, the current study focuses on posture control of the trunk using a different paradigm. We view trunk control segment by segment (as opposed to “all or none”). This approach opens up new vistas to understanding motor control in people with severe impairments [6,7].

We developed a multi-articulated trunk support system that provides external stability at a specific level of the trunk. This support enables subjects lacking independent sitting the ability to fully control head and trunk segments above the level of support against gravity and perturbations. This stabilization concept was motivated by a clinical assessment of trunk posture [12-16]) and by neurophysiological evidence that acquiring control over trunk segments is not random. Infants gain control over trunk segments in a rostral-caudal / top-down direction as they grow [12,13]. Similarly, children with CP lacking independent sitting can exhibit control over head and trunk segments when external trunk support is optimally provided[14,15]. Children with severe CP require higher levels of trunk support compared to moderately impaired patients[15,16]; and previous studies have shown children with more severe CP resemble younger infants’ posture while less severe CP resembles older infants[15]. Moving the level of support down even a few centimeters in children with moderate-to-severe CP or in typically developing infants who have not yet achieved independent sitting can result in considerable changes in posture control and loss of stability[13,15,16].

Deficits in sensorimotor processes contribute to the loss of stability in many patients lacking independent sitting [2,17,18]. Sensory integration of vestibular, visual, and proprioception information is critical for trunk posture control and the proper activation of muscles to counteract gravity and perturbations [19-22]. Previous studies have provided important insights into sensorimotor processes by observing the dynamic relationship between external stimuli and body sway responses [19,21-26]. In particular, an external surface tilt stimulus has been extensively used to distinguish contributions from the different sensory systems. During a surface tilt, the proprioceptive system orients the body toward the tilted surface

(and away from upright) while vestibular and visual feedback orient the body upright [19,22,24-26]. Similarly, during a tilt of a visual surround, the visual system orients the body toward the tilted visual surround (and away from upright) while vestibular and proprioception feedback orient the body upright [19,21-23]. By measuring the extent to which body sway either follows the stimulus or remains upright, the relative contribution of each system can be estimated. One detailed method to describe this relationship is in frequency response function gains and phases [27], where gains represent the magnitude, and phases represent the timing, of body sway response to the stimulus, respectively.

Understanding the frequency-dependent nature of posture responses is important because neural mechanisms influence posture sway differently across frequencies [19,28]. Stimulus-response posture data has also been combined with parametric system identification methods to identify abnormal scaling between stimulus and torque generation [29] and to distinguish torque generation across intrinsic stiffness, reflexes, and sensorimotor integration [19,22,25,26,28]. Because poor sensory integration, muscle weakness, or improper torque scaling can all play a role in impaired sitting, obtaining stimulus-response research data may lead to major breakthroughs in understanding detailed posture impairments. However, no previous study has developed tools necessary to incorporate this approach in populations with moderate-to-severe impairments or underdeveloped neuromotor control who lack independent sitting.

Therefore, we present a detailed description of a trunk support system that enables characterization of sensorimotor integration in populations lacking independent sitting and we demonstrate feasibility in acquiring posture data in two populations lacking independent sitting (typically developing infants and children with CP) and two populations with independent sitting (adult and children controls). Feasibility was based on the following: comfortability of subject and caregiver (physical and emotional comfort), ease of testing (short experimental set up time), adjustability to account for a wide range of body dimensions (infants to adults) and level of trunk control (axilla to lower lumbar), sensitivity to distinguish between different levels of trunk control (longitudinally in infants and across severity in children with CP), and ability to synthesize body sway and frequency response functions with clinical tests (Segmental Assessment of Trunk Control, SATCo [12] and Gross Motor Function Classification System, GMFCS) and baseline results (based on data from adults controls).

The trunk support system presented in the current study provides a window into neural mechanisms *prior to* acquisition of independent sitting. The system may serve as a model for clinicians or researchers to better understand and train many vulnerable populations that lack independent sitting.

II. METHODS

A. Design of Trunk Support System

The goal of our system was to provide frontal and sagittal plane trunk support individualized for each participant while sitting on a tilting bench. This goal required strength and rigidity of material and quick adjustability. The five main components of the system (Fig. 1A)

included 1) two vertical posts (4.3cm diameter) that could translate up and down, 2) two vertical stationary posts (6.5cm diameter) fixed to the floor, 3) two horizontal trunk supports (4.5cm diameter) with inner-ends attached to 2.5cm Dacron straps and moldable foam (3D lite-7mm, Allard International, Sweden) and polyethylene closed cell foam (AliMed, USA), 4) low friction rollers on the stationary posts for smooth vertical motion of the vertical posts (component 1) and horizontal posts (component 3), and 5) connections between components that enabled adjustability with locking screw knobs for a customized position in the vertical, frontal, and sagittal planes.

Transverse plane motion was minimized with a 6mm radius groove machined on the side of the stationary posts (component 2), which interfaced with the low friction rollers. This feature was added to counter the possibility of irregular movements that sometimes present in subjects with poor trunk control. Plastic or fiberglass was used for all components because kinematics were collected with magnetic tracking (trakSTAR, Ascension Technology, USA). Magnetic tracking was desirable so researchers could move around subjects without interfering with data capture.

The trunk support system was integrated within an articulating bench to investigate postural responses to external stimuli (tilts of a surface transmitted to the bench). The articulating bench was designed as a parallelogram with hinges between the vertical legs and top of bench, and included an adjustable foot rest. The bench interfaced with the trunk support via a connection point on the side of each leg (component 5c) that also enabled the location of the bench in the sagittal plane to be adjusted relative to the trunk support. When the surface tilted, one leg of the bench moved up and the other leg moved down. The vertical leg movements consequently moved the inside vertical post (component 1) and the horizontal post (components 3) up on one side of the trunk support and down on the other side.

Safety was considered in several ways. First, the padded strapping around the pelvis provided a comfortable and secure way to limit pelvis motion relative to the top of the bench [12]. Second, all edges near the subject were covered with soft material. Third, all components were designed for quick release using buckles on straps and screw knobs. Fourth, the bench itself had a mechanical safety stop (Fig. 1A) that could prevent bench motion in the unlikely event that more than one connection point failed. Fifth, the tilting surface servomotor system contained both automatic and manual electrical and mechanical stops for safety such that horizontal supports could not exceed ~4cm of vertical motion. Finally, ample space around the surface and trunk support system was maintained for researchers to move around during tests for spotting and behavior monitoring.

B. Human Subjects

To demonstrate feasibility, the trunk support system was tested in two control populations with no impairments (two children and sixteen adults) and two populations lacking independent sitting (two typically developing infants in a longitudinal study and four children with moderate-to-severe CP, GMFCS III-V)); see Table I. All adult subjects and parent/guardians gave their informed consent, and children over 7 years of age gave assent, before being tested using a protocol approved by the Institutional Review Board at University of Hartford.

Each test session included approximately 2 hours of posture testing with various surface tilt stimuli tests presented, of which a representative sample is presented in the Results section. Subjects were instructed to sit up and were provided a movie of their choice to watch (or listen to during eyes closed tests) on a stationary display approximately 80cm away. The display was located at eye level when subjects sat with an upright posture. For children with CP, the movie was sufficient to keep engagement and location of the display motivated upright posture. For infants, who are unable to follow verbal directions, we used age appropriate baby movies that are designed to attract attention in very young infants. In addition, it was common to supplement the movie with social interactions from parents/guardians or researchers (eg, talking, facial expressions, providing the infant colorful toys, etc.). At the start of each test session, a 2-minute surface tilt warm up test was provided.

In each test session with infants and children with CP, the level of trunk control was determined by the SATCo, which is a clinical measure of static, dynamic, and reactive posture control [12]. To complete the SATCo, the subject's pelvis is placed in a neutral vertical position and secured with straps, then a clinician provides trunk support with his/her hands at the axilla and assesses the subjects' ability to maintain head and trunk control during quiet sitting (static), during voluntary head turns (dynamic), and in response to unpredictable nudges (reactive). If trunk control is maintained in all three static, dynamic, and reactive conditions, then the level of external support is lowered. The test is repeated until the subject is unable to control their body segments superior to the level of support. There are 7 SATCo levels evenly spaced down the trunk: head control, upper thoracic, middle thoracic, lower thoracic, upper lumbar, lower lumbar, and full trunk control without any external support.

C. External Stimuli for Identification of Sensorimotor Integration

The trunk support system was incorporated into a tilting surface to deliver pre-defined external stimuli for the identification of sensory contributions to posture (Fig. 2). A Real Time Operating system (cRIO, National Instruments, TX, USA) was used to sample data at 200 Hz from a stationary frictionless potentiometer (Midori America, USA) that measured the surface tilt. The measured surface tilt was compared to the desired surface tilt stimulus. The difference between these signals went through a PID controller programmed into the Real Time Operating system, which outputted voltage to the servomotor. The servomotor rotated a steel shaft with a linear drive nut mounted to the shaft and surface, evoking high precision surface tilts. The servomotor and linkages between motor and surface were based on the design by Peterka (2002) [22]. Surface tilt stimuli were used in the current study to distinguish between contributions from different sensory systems to posture responses. When a surface tilts with respect to gravity, the proprioceptive system orients the body toward the tilted surface (away from upright) while the visual and vestibular system orients the body toward upright[19,22,24-26].

Surface tilt velocity in the present study was programmed to tilt according to a continuous pseudorandom ternary sequence (PRTS) of numbers, mathematically integrated to create the desired surface tilt position and scaled to a specific peak-to-peak value[22] (Fig. 3). The PRTS characteristics were chosen specifically for infants and children with CP. The

bandwidth was 0.046–4.9Hz, smaller than previous studies, such as Goodworth and Peterka (2009) which used 0.023–21.0Hz[19]. The smaller bandwidth was considered more suitable for our population because this bandwidth was gentler (less power across higher frequencies). In addition, the PRTS waveform was only 21.78 s so that many repetitions of the waveform (typically ranging from 8-12) could be delivered to subjects during each test. Repeating waveforms is important to accurately estimate posture responses[22-26], detect adaptation[22,25], and correlate posture with behavior coding for categorization within each waveform[15].

D. Trunk Support Dynamics Analyses

Trunk support dynamics were characterized through the relationship between surface tilt motion and horizontal trunk support motion (component 3). High resolution vertical motion of the horizontal supports was obtained using a potentiometer and “sway rod”[30]. The “sway rod” was attached to the stationary frictionless potentiometer (Midori America, USA) on one of its sides and attached to the horizontal trunk support on the other side. Trunk support motion thus moved the sway rod up and down which rotated the potentiometer. Frequency response functions (gains and phases) and coherence functions were calculated between surface tilt and vertical motion of the horizontal supports. Goodworth and Peterka (2009) provides a detailed description of these frequency-based measures[19]. In brief, gains and phases indicate the relative magnitude and timing, respectively, between surface tilt and horizontal support motion as a function of frequency. Coherence reflects the degree of linearity between surface tilt and horizontal support motion, where a coherence of one indicates a perfect linear relationship in the absence of noise. Confidence intervals with 95% confidence level on gains and phases quantified the repeatability of surface to trunk support motion [31].

E. Human Subject Analyses

Data were obtained using magnetic sensors placed on a headband and on the trunk over the spinous process of the seventh cervical vertebrae (C7) (Fig. 1B). For brevity, only C7 data are presented. Motion at C7 was converted to frontal plane trunk sway with respect to gravity by normalizing motion of the sensor by the vertical distance to the horizontal trunk support. This method models the trunk as an inverted pendulum rotating above the level of support. Frequency response functions were calculated between trunk sway and the surface tilt. A gain of one indicates trunk alignment to the surface tilt and a gain of zero indicates the body is upright. Zero-meaned root-mean-square (RMS) measures were calculated across each test. An 8° peak-to-peak PRTS test was repeated in each session (at the start and randomly placed ~10-45minutes after) to assess repeatability/adaptation in RMS sway between repeated tests using a paired T-test.

To address subject and parent comfort, qualitative feedback was obtained through informal open-ended conversations with parents/guardians. Because our subject population often lacks verbal communication, it is critical that attention is given to behavior (extraneous movements, facial expressions, fussy, fidgety, etc.). We videotaped every session and visually monitored subjects' behavioral cues during testing [15].

III. Results

A. Dynamics and Adjustability of Trunk Support System

Figure 4A illustrates a surface tilt stimulus and corresponding motion of the trunk support translation in the vertical direction averaged across ten repeated surface tilt waveforms. There was a very high correlation between the vertical trunk support motion and surface tilt across the entire test ($R=0.99$). 95% confidence intervals are denoted in grey, nearly imperceptible in Fig. 4A. Gains were nearly constant and phases were approximately zero at frequencies up to 5Hz (Fig. 4B). Error bars on gains and phases represent 95% confidence intervals across repeated PRTS waveforms. Coherence remained essentially one up to about 2.5Hz and was 0.97 at 5Hz. Taken together, dynamic analysis of the trunk support system showed that surface motion was transmitted to the supports accurately up to about 5Hz.

When positioning a subject in the trunk support system, numerous adjustments were needed for proper alignment in all three planes of motion. The quick adjustability of knobs and sliding parts helped reduce set up time to less than 5 minutes for all subject groups.

B. Sample Infant Data

All behavioral cues and parent/guardian feedback indicated that the pseudorandom surface tilt waveform were comfortable and often preferred over quiet sitting. Figure 5A presents trunk sway from a six-month infant lacking independent sitting. In both the top plot (support at SATCo level) and middle plot (support at one SATCo level lower), trunk sway is in response to an identical 8° peak-to-peak surface tilt. Trunk sway generally followed the stimulus in both conditions, but a large increase in sway (nearly double RMS) is evident when support is placed lower on the trunk.

The longitudinal infant tests included 8 test sessions over 4 months. In Fig. 5B-D, the trunk support level coincides with the SATCo and is therefore progressively reduced with increasing age and increasing test session. In quiet sitting, RMS trunk sway did not show systematic changes across test session (Fig. 5B), but there was a clear decrease in RMS sway in response to the 8° stimulus, suggesting that the perturbed test condition offers unique view of the changing posture system compared to quiet sitting alone. Gains to the 8° stimulus were generally lower across all frequencies measured (0.046–2Hz) when comparing responses at the fourth month session to the first in the sample infant. Gain at the lowest frequency dropped from ~ 4 to 1 across four months. Also, greater development was associated with phase leads at low frequencies and more phase lag at high frequencies. The second infant tested in the longitudinal study showed similar trends in gains and phases (data not shown). Adaptation was not detected within each session as neither infant displayed statistically significant change in RMS sway between the randomly repeated tests delivered in the same session. Taken together, the trunk support system and associated stimulus-response data were sensitive to changes across development.

C. Sample Data from Children with Moderate-to-severe CP

Using the trunk support system, it was also feasible to obtain data from children with CP lacking independent sitting. Similar to infants, a summary of behavior cue, parent/guardian

feedback, and (in some cases) subject verbal feedback indicated that the pseudorandom surface tilts were comfortable and often preferred by subjects over quiet sitting.

Figure 6 shows trunk responses from four children (GMFCS level V is averaged across two children). Based on SATCo results, children in GMFCS level IV and V (most severe) were provided trunk support at the axilla while the child in GMFCS level III was provided support at the lower ribs. Frequency response function gains (8° peak-to-peak stimulus) from children in the GMFCS level V category were noticeably higher and more variable across frequency than GMFCS level III and IV (Fig. 6A&B). The child at GMFCS level III exhibited a relatively small gain accompanied by a phase lead at the lowest frequency, similar to data observed in the two infants at about 5-6 months of age (~ 3 -4 months post testing, Fig. 5C&D). Also, the decrease in RMS sway across GMFCS levels in response to the 8° stimulus (Fig. 6D) mimicked the decrease in RMS sway in infants across maturation (Fig. 5B).

D. Control Testing

Control data created a baseline for comparison of kinematic data and helped determine if the system was adjustable to a wide range of subject dimensions. Qualitative feedback from the 16 adults and 3 children (tested at various levels of trunk support) confirmed that the system has adequate adjustability and comfort to collect data across a range of trunk dimensions from infants to adults. Adult data from one representative subject shows the gain and phase curves with and without trunk support at lower thoracic (Fig. 7). With support, gains and phases were more constant across frequencies below 1Hz compared to without support. Without support, phase lags above 0.8Hz were more evident compared to with support. Coherence was typically above 0.8 at frequencies below 1Hz with and without support.

IV. Discussion

Populations lacking independent sitting typically present with complex clinical features and severe motor deficits which exclude them from most research studies[6,7]. However, trunk control and postural alignment is critical for basic daily activities[32]. Even slight variations in postural alignment create changes in upper extremity skills[16,18,33]. Many people lacking independent sitting may in fact possess partial posture control when their trunk is supported. Therefore, we developed a trunk support system that provided external stability at a specific level on the trunk to 1) help understand mechanisms of neural control and 2) enhance clinical rehabilitation in populations lacking independent sitting. Below is a discussion of research and clinical implications.

A. Trunk Control Research in Patients Lacking Sitting Ability

The trunk support system was integrated within a moving surface conveyed tilts accurately and consistently up to 5Hz (see small 95% confidence intervals in Fig. 4B), supporting validity and repeatability across repeated surface tilt waveforms. Feasibility was assessed in several ways. First, comfort was established via informal qualitative feedback and behavior monitoring in all populations. Many subjects preferred the surface tilt stimuli over quiet sitting. The quick adjustability in the system contributed to this comfort as positioning and

set up time was less than 5 minutes. Second, the system comfortably accommodated a wide range of body dimensions (ranging from infants to adults) and a wide range of trunk control (ranging from those requiring support at axilla to control subjects with independent sitting).

Third, the system was sensitive to differences in trunk control across severity of CP (GMFCS levels III-V) and development in typically developing infants. With support at the SATCo level, subjects maintained posture against gravity and perturbations, however, below the SATCo level, sway has been shown to increase for infants and children with CP [15]. We found that RMS sway and gains became less variable across stimulus cycle and were lower in magnitude in individuals with less severe CP and in older infants. The similarity in posture between severity of CP and development in infants was anticipated because previous studies have shown that children with more severe CP resemble younger infants while children with less severe CP resemble older infants [12,15].

Fourth, RMS and frequency response functions were consistent with clinical tests and control data. In infants, RMS sway was not significantly different between the start and end of each testing period, consistent with adult data and previous studies [22,34]. Infants and children with CP also exhibited similar trends in frequency response functions curves. Specifically, phases were relatively constant at lower frequencies (<0.5 Hz), showed more phase lag as frequencies increased above 0.8 Hz, and gains were generally lowest at the higher frequencies (>1 Hz). Also, subjects with the poorest trunk control (GMFCS level V and young infants) exhibited large and variable responses to stimuli (Fig. 5, 6) whereas adult control subjects exhibited low variability and small gains (Fig. 7). The infant tested at the 4th month of the longitudinal study (Fig. 5C) showed a very similar gain curve to the adult control subject with no support (Fig. 7, top). But in general, subjects with moderate trunk control (GMFCS level III, IV, and older infants) displayed behavior in-between adults and those with the poorest trunk control.

Obtaining stimulus-response posture data have established benefit for understanding mechanisms of posture control [19,21-26]. When investigating mechanisms of posture control, it is beneficial to evaluate trunk responses across multiple frequencies because the influences of specific neural and biomechanical mechanisms are most evident across specific frequencies[19,22,25,26,28]. One example of a frequency-dependent neural mechanism can be seen in data from infants and children with CP. The two infants exhibited a decrease in gain accompanied by phase leads at the lowest frequencies (<0.1 - 0.2 Hz) with maturation. Similarly, the least severely involved child with CP exhibited similar gain and phase features while the remaining children with CP (more severely involved) did not. In previous modeling studies, these experimental gain and phase features were explained through the contribution of a force-encoding sensory feedback mechanism (presumably of Golgi-tendon origin) that primarily affects postural control at lowest frequencies[19,26,28]. If future studies in infants and children with CP consistently reveal maturation- and severity-dependent changes at low frequencies, and if these changes are also attributable to force feedback, then rehabilitation using force feedback from proprioceptors in the trunk may be one key to establishing functional improvement in patients with moderate-to-severe CP.

In infants, the change in RMS across increasing test session was consistent with lower gains across a wide range of frequencies (0.046–2Hz) suggests a nonlinearity in the infant posture control system across development. Similar nonlinearities have been seen in adults when increasing surface stimulus amplitudes evoke decreases in frequency response function gains across a similar range of frequencies. Modeling studies attributed these decreases in gain to a greater use of vestibular feedback [22,26,28]. Future studies in infants and children with CP would need to test this hypothesis.

B. Clinical rehabilitation and customization

Concepts behind the trunk support system have direct clinical impact for children with moderate-to-severe CP (lacking independent sitting). While historically almost no physical rehabilitation training has been widely used for these children, in recent years, clinical researchers have begun documenting improvement by exploiting the concept of “segmental training”[14,35-37]. In segmental training, similar to the current study, children are first assessed for their current level of trunk control using the SATCo. Then, participants are positioned in a trunk stabilization device and practice daily trunk and arm movements at home. As participants gain greater trunk control, clinicians progressively lower the support level on the training device. Given the positive initial reports from segmental training[14,35,36], we propose that the trunk support system in the current study is ideally suited to identify mechanisms of motor learning and sensorimotor integration that underlie improvements with training. Numerous factors could improve with training (sensory integration, muscle strength, stimulus-to-torque scaling, etc.) and the current stimulus-response sensory conflict approach may help identify which mechanisms improve. In addition, with modest reconfiguration, the trunk support system could be incorporated into the “sensory organization test” [38], which is a computerized clinical assessment of sensory reliance which uses surface and visual surround tilt stimuli but is currently only available for persons who are able to stand independently.

Several motor learning concepts support the idea of providing external trunk support. First, external support promotes activity; and activity provides the growth of white matter, potentially offsetting the documented reduction in white matter in children with CP [39]. Activity also provides the opportunity for meaningful sensory and performance errors that drive plasticity [40]. Second, biomechanical support enables practice of upright posture against gravity without needing to use severe compensatory patterns. For some populations, such as children with severe CP, this may be the first time using vision and vestibular feedback to specifically control posture against gravity. With extended periods of sensory feedback pertinent to posture control of the trunk, it is reasonable to suppose that the nervous system will alter its sensorimotor integration processes to more optimally use available information. Finally, the external support reduces the degrees of freedom in the trunk that need to be controlled [37], which might simplify the task [41].

C. Limitations and challenges

External stimuli directly evoked sway in the frontal plane while 3-D kinematics were obtained. It would be valuable to also use a perturbation to directly evoke sway in the sagittal plane. A visual stimulus could be incorporated into the current trunk support

configuration; however, a significant redesign would be required to deliver a surface perturbation [34]. We also note that our qualitative assessment of comfort may benefit from the creation of a standardized assessment. Furthermore, during perturbations, subjects could lean forward or backwards, potentially as a compensation strategy when feeling challenged or unmotivated. The current strapping system, though required for safety, does permit leaning above the level of support during our tests. This underscores the importance of selecting an appropriate level of support and providing motivation for upright posture. We are designing a backboard system to eliminate this potential compensation and thus isolate posture control against gravity [22,24,25].

Testing infants and children with moderate-to-severe CP present unique movement-based research challenges. Standard balance measures (such as RMS trunk sway) may not capture the performance goals of severely impaired populations. For example, one patient in GMFCS level V was retested during a posture training intervention study. Behavior monitoring revealed the subject was able to visually focus on the computer monitor in front of him/her better than the previous test session, yet trunk sway measures were not different between sessions. In this case, gaze stability or head kinematics may better reflect changes in neural control. Another challenge is the presence of extraneous movements (sometimes unrelated to posture control) which ultimately reduce confidence in quantitative measurements of posture. One advantage of our stimulus-response approach is that movements at stimulus frequencies can be measured independent of other frequencies where movements may occur. If the variability of movements are unbiased and random, then averaging across repeated stimulus cycles will minimize this variability [27]. Finally, additional insight into segment motion may be gained by exploring sensorimotor noise evident at non-stimulated frequencies [42] or utilizing nonlinear analyses [11,43].

D. Conclusion

The proposed trunk support system was successfully integrated within a tilting surface. System dynamics were accurate up to 5Hz. We demonstrated feasibility by comfortably testing a wide range of subjects (infants and children lacking independent sitting to adult control subjects), providing evidence that trunk control can be maintained during continuous external surface stimuli when support is provided, and presenting preliminary evidence that important mechanisms of trunk control can be identified in infants and children with CP who lack independent sitting. To our knowledge, this is the first description of an articulating trunk support system that can be used for studying sensory contributions to trunk control in populations lacking independent sitting.

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Fig 1.

A) Image of trunk support system and bench. Distance between inside vertical translating posts (1) was 55cm. Length of outside stationary post (2) was 110cm. Bench height was 60cm, width was 46cm, and depth was 30cm. B) Schematic of infant on bench showing sensor placement and angle definitions.

Fig 2.

Schematic of trunk support system integrated within a tilting surface. The tilting surface was controlled by a Real Time Operating system, programmed with proportional, derivative, and integral (PID) control, where voltage output was based on the difference between the desired and measured surface tilt (measured with a potentiometer attached to the axis of the surface).

Fig 3.

Surface tilt characteristics determined by pseudorandom ternary sequence (PRTS), where each number in the PRTS waveform determined a tilt angle velocity of either +“a”, 0, or –“a”. The value of “a” was scaled up or down depending on the desired peak-to-peak amplitude and was maintained constant for a specified duration of t s. The t was 0.09 s and the PRTS waveform lasted 21.78 s for tests with infants and children with cerebral palsy.

Fig 4.

Dynamics of the trunk support system. A) Surface tilt and trunk support motion in time and B) Frequency domain characterization of trunk support system. 95% confidence intervals across repeated waveforms are displayed in grey for both time and frequency domain measures (nearly imperceptible using the current scale).

Fig 5.

A) Sample infant data shows marked increased in root-mean-square (RMS) trunk sway when lowering trunk support by ~5cm. B) RMS versus test session in one infant in the longitudinal study for quiet sitting (0° surface tilt) and perturbed (8° surface tilt). C and D) Frequency response function gains and phases at the first and fourth month of testing of one infant during an 8° stimulus. Error bars represent 95% confidence intervals across repeated stimulus waveforms.

Fig 6.

Sample trunk sway data from four children with moderate-to-severe cerebral palsy A) Frequency response function gains to 8° stimulus for all four children (GMFCS V values are average of two subjects). B) Gain at lowest frequency across GMFCS categories. C) Frequency response function phases. D) RMS trunk sway versus GMFCS category for quiet sitting (0° surface tilt) and perturbed (8° surface tilt).

Fig 7.

Sample trunk sway data from one adult control subject expressed in frequency response function gains and phases to 6° peak-to-peak pseudorandom stimuli for sitting with external support at lower thoracic and sitting without any external support in eyes closed.

Table I

Range of subject demographics tested with the trunk support system

	Infants tested 2×/month for 4 months (N=2)	Children with CP at GMFCS levels III, IV, V (N=4)	Children controls with independent sitting (N=3)	Adults controls with independent sitting (N=16)
Age (yrs)	0.2 - 0.7	3 - 11	5 - 9	18 - 63
Height (cm)	60 - 70	97 - 137	118 - 130	150 - 186
Weight (kg)	5.7 - 8.2	13 - 39	22 - 31	61 - 87

Numbers are minimum-maximum ranges for each category.