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Evaluation of a Transparent Seat Back for Motion Capture of the Thoracolumbar Spine on the Multi-Axis Ride Simulator

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14. ABSTRACT
Low back pain is a pervasive health problem in a range of military occupations. A knowledge gap exists regarding spinal movement in operational ride environments due to limitations in data collection caused by equipment impeding motion capture data collection. This involves the development and validation of a novel transparent seat back (TSB) for the USAARL multi-axis ride simulator (MARS) to develop a standard methodology to quantify seated spinal motion response to whole-body vibration (WBV) and jolt during simulated operational transport environments. The TSB was fabricated and affixed to the standard MARS chair instead of the aluminum seat back. Volunteers were instrumented and asked to perform torso movements within all three planes. Vicon motion capture was used to observe visual distortions through the transparent seat back. Data were collected for a 35th percentile female and 95th percentile male, and *x*-, *y*-, and *z*-positional data were analyzed. Results indicate that the retroreflective markers can be tracked regardless of TSB configuration with minimal error or distortion. The TSB will add to vibration research capabilities.

15. SUBJECT TERMS
low back pain, LBP, military back pain, whole-body vibration, WBV, motion capture, Vicon, transparent seat back, seated spinal kinematics, spinal motion, spinal motion capture, thoracolumbar spine

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Summary

Low back pain is a pervasive health problem in a wide range of military occupations. Presently, a knowledge gap exists regarding spinal movement in operational ride environments due to limitations in data collection caused by equipment impeding motion capture data collection. The U.S. Army Aeromedical Research Laboratory (USAARL) multi-axis ride simulator (MARS) is a unique motion platform capable of replicating aircraft and vehicle ride signatures to apply whole-body vibration (WBV) exposure. The MARS is currently equipped with an aluminum chair with an adjustable reclining seat back and seat pan to mimic seating geometries across a variety of vehicles. Spinal kinematic assessments involving motion capture in the existing MARS chair are limited to the cervical spine due to the opaqueness of the chair's solid aluminum seat back. For this test, USAARL researchers developed and evaluated a novel transparent seat back (TSB) for the USAARL MARS that can be used to develop a standard methodology to quantify seated spinal motion response to WBV and jolt during simulated operational transport environments. The TSB was fabricated and affixed to the existing MARS chair base and seat back support structures in place of the aluminum seat back. Motion capture sequences were performed with retroreflective markers positioned statically against the TSB and through controlled movements using a stadiometer. Additionally, volunteers were instrumented and asked to perform torso movements within all three planes. Vicon motion capture cameras were used to observe potential visual distortions through the TSB in different configurations (TSB configurations), in which the TSB recline angle and seat back support structures were varied. Data were collected for a 35th percentile height female and a 95th percentile height male; *x*-, *y*-, and *z*-positional data were exported from the Vicon motion capture system for analysis. The results indicate that regardless of TSB configuration, the retroreflective markers can be tracked with minimal error or distortion in a stationary environment. The development of the TSB provides a necessary capability for the advancement of operationally relevant musculoskeletal and WBV research in dynamic military environments.

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Table of Contents

List of Figures

Table of Contents (continued)

Page

List of Figures (continued)

List of Tables

Introduction

Spinal disorders, including low back pain and interverbal disc disorders, are common occurrences associated with occupational exposure to whole-body vibration (WBV) (Bovenzi & Hulshof, 1998; Dupuis & Zerlett, 1987; Harrer et al., 2005). Due to the changing multi-domain operation landscape and the increase in the frequency of extended-duration missions, spinal disorders are of interest to Service Members (SMs) in the military where occupational exposure to WBV is commonplace among some military occupational specialties (MOSs), such as those involving aviation and ground vehicle transport. Additionally, vehicle vibration exposures can be compounded by random jolts or impacts produced by rough terrain, turbulent air, or aggressive maneuvers. The work of the cervical spine musculature in seated postures to maintain an upright, neutral posture of the head and neck during WBV exposure places a powerful force on the lower cervical spine. The combination of this force and the increased loading from WBV exposure have contributed to spinal disease, disorders, and even injuries over a long period of repetitive exposures, such as a career in a WBV environment (Dupuis & Zerlett, 1987).

Rotary-wing WBV exposure has been shown to correlate with unique lumbar spine pathology, with helicopter pilots demonstrating lumbar intervertebral disk degeneration different from, and at a younger age than, fixed-wing pilots (Landau et al., 2006). Additionally, aviators experience back injuries, such as lower disc herniation, at a rate of 1.22 times higher than their non-pilot counterparts (Knox et al., 2018). Understandably, aviators report high rates of spinal pain. A survey conducted by Andersen et al. (2015) found that 67% of rotary-wing aviators, who had been exposed to WBV in flight, reported that they experienced spinal pain over the prior 12 months, either during flight or recurrent after a pain-free month, or both. Outcomes from a military survey found that 73.6% of study participants with exposure to ground armored vehicles (tracked and wheeled, within the past 12 months) reported low back pain; the reported low back pain was higher among tracked armored vehicle drivers (Rozali et al., 2009). In the same study, the WBV exposure in tracked armored vehicles was greater in comparison to wheeled armored vehicles. The potentially hazardous effects of long-term ground vehicle WBV exposure on the spine have driven previous efforts from the U.S. Army Aeromedical Research Laboratory (USAARL) to develop health hazard assessments for these environments (Alem et al., 2004; Alem et al., 2005). However, spinal disorders continue to be an issue, as SMs in MOSs associated with military ground vehicle exposure seek treatment for back pain and injury more than SMs in functional support and administrative MOSs (Defense Medical Epidemiological Database, 2016-2022). With such significant rates of spinal disorders being reported, it is necessary to understand spinal kinematics during seated WBV exposures that are representative of real-world WBV scenarios.

The muscular system plays an important role in the mitigation of vibration by serving as a supportive dampening system. Vibration exposures occur predominantly to individuals in a seated posture, with vibrations transmitted from the seat directly into the spine through the pelvis. The spine is the primary musculoskeletal component of interest regarding WBV exposure because of its role in both supporting the weight of the individual and reducing the transmission of vibrations throughout the body. The principal resonance frequency of the upper body while seated during vertical WBV is 5 Hertz (Hz) (Griffin, 1996). De Oliveira & Nadal (2005) found pilots experience vibrations between 4.5 and 5.3 Hz at the third lumbar (L3), first thoracic (T1) vertebrae, and seat pan when exposed to the 3 to 7 Hz vibration produced by a helicopter.

Significantly higher transmissibility values (acceleration responses) were observed at T1 than at L3 or the seat pan (De Oliveira & Nadal, 2005). This observation suggests that WBV transmission may produce a larger response through the spine of the aviator than other parts of the body or chair. Additionally, it has been found that the frequency response of the spine is non-linear; there were higher frequencies in the lumbar spine than in the pelvis (Mansfield & Griffin, 2000). The non-linear nature of spinal transmissibility in the human body may contribute to larger responses that are associated with spinal injury, suggesting that the spine may be more susceptible to injury when exposed to WBV.

A key component in examining the link between WBV exposure and spinal disorder is to characterize the spinal kinematic response to vibrations. While prior spinal transmissibility research has examined the kinematics of individuals in a seated position, these studies have done so either with a backless chair or with limited use of motion capture techniques. A benefit of standard seating systems is their ability to encourage operationally-relevant postures through the inclusion of a seat back as well as a restraint system. A limitation of these standard seating systems, though, is the propensity for the opaqueness of a standard seat back to obscure a large portion of the spine, thereby limiting the ability to assess spinal kinematics of the whole spine, specifically the thoracolumbar region. Studies with standard seating systems have used sensors such as accelerometers to examine spinal transmissibility (e.g., Barazanji & Alem, 2000; De Oliveira & Nadal, 2005); however, these sensors directly measure acceleration and require additional calculations to determine displacement. Motion capture of seated spinal kinematics allows for direct capture of positional data in an established coordinate system relative to other applied markers in the capture space. Motion capture has been used in spinal transmissibility research, but these studies have typically used backless chairs (e.g., Dupuis & Zerlett, 1986; Seroussi et al., 1989; Village et al., 1995; Baig et al., 2014), which are not representative of air or ground vehicle seating systems, where WBV exposures typically occur. Furthermore, the presence of a back support has been shown to have an influence on spinal transmissibility (Wang et al., 2006). A three-dimensional motion capture protocol was developed for a seating system with an opaque back (Rahmatalla et al., 2008); however, this methodology relied on assuming segments of the spine behaved as rigid bodies, which is counterintuitive to examining the propagation of vibratory response through the spine.

Prior research at USAARL has assessed the head and neck response to WBV exposure in conjunction with head-supported mass use (Butler, 1992; Alem et al., 1995; Butler & Alem, 1997; Barazanji et al., 1998; Barazanji & Alem, 2000). USAARL has additionally developed a methodology for conducting health hazard assessments of WBV exposure from military ground vehicles (Cameron et al., 1998; Alem et al., 2004; Alem, 2005). This work has been conducted with the USAARL multi-axis ride simulator (MARS), a unique motion platform capable of replicating vibration signatures from aircraft and ground vehicles (Chancey et al., 2007). While this work has contributed knowledge on health effects from WBV exposure and led to improvements in ISO 2631-5 (2004; Cameron et al., 1998), this groundbreaking work was conducted with a backless seating system, which allowed motion capture of total or segmental spinal kinematics but not necessarily in an operationally-relevant seated posture for today's military vehicles and aircraft. The capability of full optical spinal kinematic motion capture in an operationally-relevant seated posture has been missing to this point.

The existing MARS chair was developed to provide a controlled, repeatable WBV exposure to volunteers. It has a rigid, adjustable seat back and seat pan, constructed of solid aluminum, to allow the replication of a wide variety of vehicle seat geometries, allowing volunteers to adopt operationally-relevant seated postures. The existing seat back excels at its initial design goals; however, it does not allow for motion capture tracking of retroreflective markers attached to a volunteer's lumbar and thoracic spine. While there are several engineering solutions to this issue, the two most commonly proposed solutions are a slotted seat back or a transparent seat back. A slotted seat back, an otherwise solid aluminum seat back with an opening along the spine, has several drawbacks, including structural stability during vibration exposures, the challenge of accommodating the range of female and male anthropometry, and the inability to ensure clear line-of-sight for required optical markers through the range of seating orientations and human movement. In contrast, a full-sized transparent seat back (TSB) could allow for the capture of kinematics along the entire spine with a seat back present during WBV exposure without impeding the view of motion capture devices. Such a design would allow for organic movement of the spine and kinematic posture as it would naturally occur in a traditional seated WBV exposure in military air and ground vehicles.

The purpose of this effort was to develop a seat back made of transparent material and evaluate its potential to collect thoracolumbar spine kinematics during future laboratory-based human volunteer characterization studies involving the use of the MARS to create simulated dynamic exposures. The development of the TSB provides a necessary capability for the characterization of spinal response to operationally-relevant WBV exposures. The ability to characterize spinal response along the entire spine of the seated occupant in an operationally-relevant posture during WBV exposure using the TSB will greatly benefit ongoing and future USAARL research and modeling efforts targeted at assessing injury risk and mitigation strategies in dynamic military environments.

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Methods

The present effort was determined not to be research by the USAARL Determination Official. The work was conducted under a non-research protocol reviewed and approved by the USAARL Regulatory Compliance Office. The USAARL Fabrication Shop created an alternate TSB made of clear Lexan™ polycarbonate (Sabic, Pittsfield, MA.) This TSB has the same dimensions (733.5 millimeters [mm] in length by 652.5 mm in width) as the existing aluminum seat back on the MARS chair, with the exception of thickness; the thicknesses of the TSB and aluminum seat back are 12.7 mm and 9.5 mm, respectively. The TSB was made thicker to increase its stiffness, as Lexan™ (modulus of elasticity = 2.3 gigapascals [GPa]) is more flexible than aluminum (modulus of elasticity = 69 GPa). Braces and support hardware were attached to the TSB in the same locations as the aluminum seat back (Figure 1).

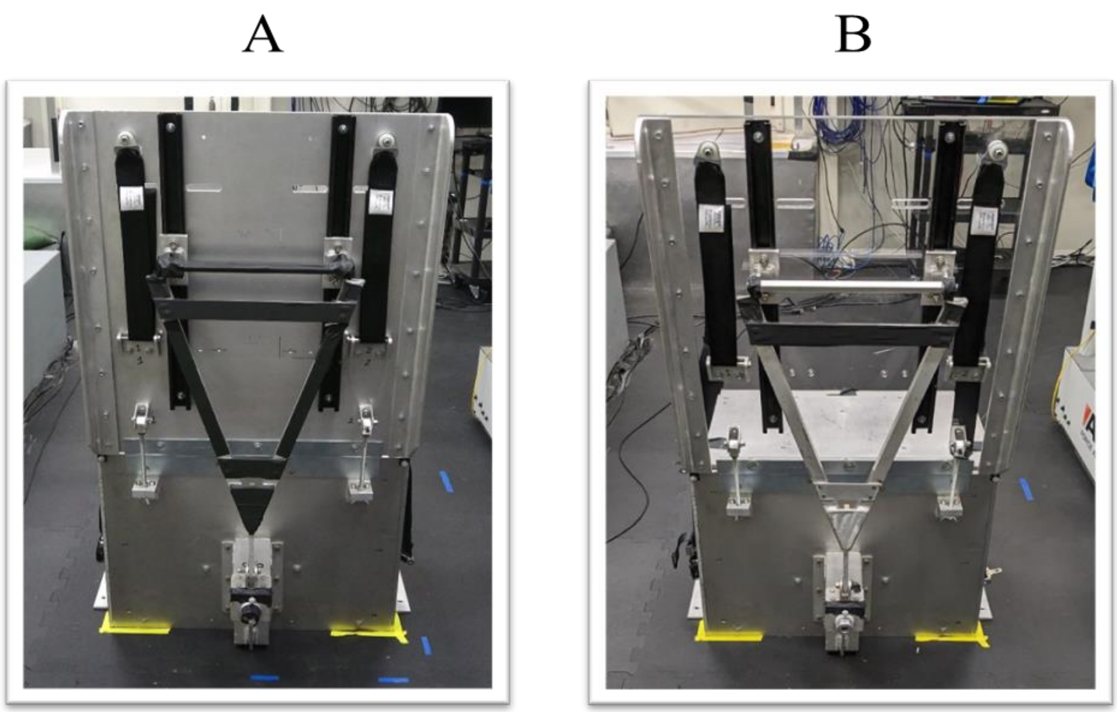

Figure 1. The MARS chair with the (A) existing aluminum seat back retrofitted with a (B) TSB of the same dimensions (except thickness) to investigate whether optical tracking of spinal motion was possible.

In this proof-of-concept effort, a variety of motion captures, of moving and non-moving retroreflective markers through and around the stationary TSB chair, were conducted to gauge the effects of the TSB on the determined marker positions by the Vicon (Vicon, Oxford, United Kingdom) motion capture system (Figure 2; Table 1). A motion capture starts with the recording of moving or non-moving markers by an optical motion capture system. After camera recording, subsequent processing of marker position per recorded camera frame calculates the location coordinates of each marker within a defined real-world space. In this work, the terms “motion capture,” “motion capture sequence,” and “capture” will be used interchangeably to refer to the entire process of recording and processing to define the location coordinates, and thus the motion (or lack of motion), of each marker in three-dimensional space.

Capture sequences (Table 1) were conducted with static retroreflective markers initially, followed by markers positioned and moved along a fixture (a repurposed stadiometer from an anthropometry kit; Figure 4. A stadiometer is a useful tool for measuring linear distances; it consists of a square metal tube inscribed with a millimeter ruler and a measuring branch holder which slides along the tube to facilitate reading of the ruler. A stadiometer is typically used to measure volunteer height or linear anthropometries. Finally, captures were conducted with markers placed on the vertebrae of members of the USAARL research staff. A combination of four motion capture cameras, three Bonitas, and one Vero (Vicon, Oxford, United Kingdom), were used during all capture sequences (initial captures, stadiometer movement captures, and human volunteer captures). The cameras were positioned approximately 2387.6 mm behind the chair and aimed at the TSB. A diagram of the camera positions is in *Figure 2*. Prior to capture sequences, the cameras were calibrated using the system's active calibration wand. During calibration, the wand was moved through the capture space so that the cameras had a view of the wand above, beside, and through the TSB.

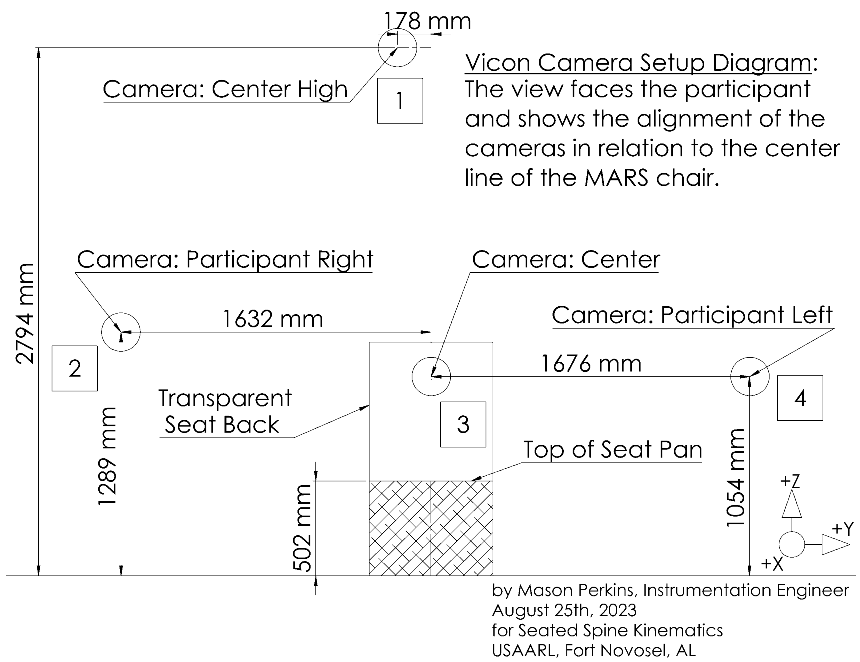

Figure 2. Vicon motion capture cameras (numbered 1 through 4) were positioned on a wall approximately 2387.6 mm behind the chair to examine the effect of camera angle on marker positioning through the TSB. Camera measurements relative to the chair centerline are provided.

Capture Sequences

A total of three assessments were conducted to evaluate the motion capture camera's ability to collect positional data from retroreflective markers through the TSB. An initial capture sequence was taken to determine if there was an effect on marker positional data based on camera angles when captured through the TSB. Next, a stadiometer movement capture sequence was taken to determine the ability to track known moving distances through the TSB. Lastly, a human volunteer capture sequence was conducted to determine the feasibility of tracking markers on people and to establish lateral and forward limits of the TSB design.

Five different configurations of the TSB were used during the motion capture sequences: backless, upright, upright with brace, 15-degree recline, and 15-degree recline with brace. While the cross-brace adds support to the seat back during vibration exposures, it can hinder the tracking of spinal markers. Therefore, captures were conducted with and without the cross-brace attached. Additionally, the seat back can be reclined at an angle to match different vehicle seating orientations. Captures were conducted with the TSB in an upright, vertical position and at a 15-degree recline from vertical. Fifteen degrees was considered to encompass a range of military vehicle seating systems as recline angles of the UH-60 Black Hawk and Mine-Resistant Ambush Protected (MRAP) ground vehicle seating systems are less than 14 degrees. The configurations of the TSB used for the motion capture sequences are included in Table 1.

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Table 1. Motion Capture Sequences and TSB Configurations

	Capture sequence	TSB configuration	Data collected
Initial captures	Three markers were placed in a vertical line on a rigid foam board. A capture was first taken with all cameras enabled, followed by four captures with a single camera disabled sequentially from camera 1 through camera 4	upright back with brace	Static trials: • all cameras • camera 1 disabled • camera 2 disabled • camera 3 disabled • camera 4 disabled
Stadiometer movement captures	Stadiometer perpendicular to the seat pan with two measuring branch holders starting at 50 centimeters (cm) (500 mm) and 25 cm (250 mm) above the seat pan. The top measuring branch holder was moved down until contacting the bottom measuring branch holder (80 mm between markers). Both measuring branch holders moved together until reaching the lowest positions on the stadiometer, approximately 174 mm and 94 mm	backless	Two stadiometer moving trials per TSB configuration
		upright back	
		upright back with brace	
		15-degree back	
		15-degree back with brace	
	Same as the previous stadiometer movement capture, only with the base of the stadiometer on a wedge to angle the stadiometer 10 degrees from vertical in the lateral direction	backless	Two stadiometer moving trials per TSB configuration
		upright back	
		upright back with brace	
		15-degree back	
		15-degree back with brace	
Human movement captures	95^{th} percentile male	backless	One static trial and three of the following movement trials per TSB configuration: • left lateral bend • right lateral bend • forward flexion
		upright back	
		upright back with brace	
		15-degree back	
		15-degree back with brace	
	35^{th} percentile female	backless	One static trial and three of the following movement trials per TSB configuration: • left lateral bend • right lateral bend • forward flexion
		upright back	
		upright back with brace	
		15-degree back	
		15-degree back with brace	

Initial captures.

Initial captures to evaluate the effects of the TSB on marker positions were taken with static markers positioned against the TSB. Three retroreflective markers (markers 1, 2, and 3) were placed in a vertical line on a rigid foam board in a manner similar to markers being placed on a volunteer's spine (Figure 3). The objective of the initial captures was to determine if there is an effect on marker positional data based on camera angles when captured through the TSB. A capture was first taken with all cameras enabled, followed by subsequent captures with one of the four cameras disabled. Reported distances were captured from the following camera arrangements: cameras 1, 2, 3, and 4 (all cameras); cameras 2, 3, and 4 (camera 1 disabled); cameras 1, 3, and 4 (camera 2 disabled); cameras 1, 2, and 4 (camera 3 disabled); and cameras 1, 2, and 3 (camera 4 disabled). One five-second capture was taken for each camera arrangement. All the samples within each capture were averaged to give the mean distances between the markers for each camera arrangement. The mean differences between all cameras and each arrangement when one camera was disabled were calculated. As all cameras were positioned at different angles from the TSB, a change in marker positional data could occur due to a refraction or another optical distortion due to tracking angles.

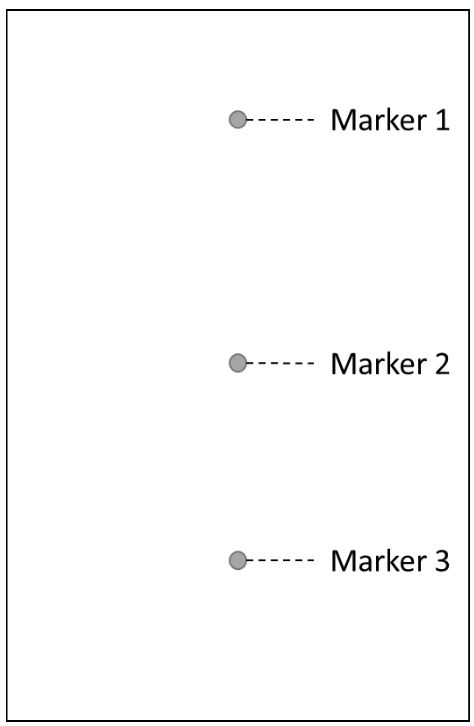

Figure 3. To gauge the effect of camera angle on marker positional data when captured through the TSB, three markers were positioned in a vertical line on a rigid foam board and placed against the TSB. Captures were taken with all four cameras enabled followed by subsequent captures, each with one of the cameras disabled.

Stadiometer movement captures.

Stadiometer movement captures were conducted by attaching retroreflective markers to a stadiometer and practicing controlled movements. The objective of this capture sequence was to determine the ability to track known moving distances through the TSB. The stadiometer is a versatile instrument that can be used to measure almost any linear dimension. It is a square pole that consists of four interconnecting metal tubes, with two surfaces that are engraved in millimeter intervals. The measuring branch holder, which can slide up and down the pole, has a scale reading window, allowing the operator to read the numerical value of a measurement quickly and precisely to the nearest millimeter. One Vicon marker with a 14 mm sphere and a flat base was attached to each of two measuring branch holders, with the midline of the marker aligned with the measurement mark in the middle of the scale reading window (Figure 4).

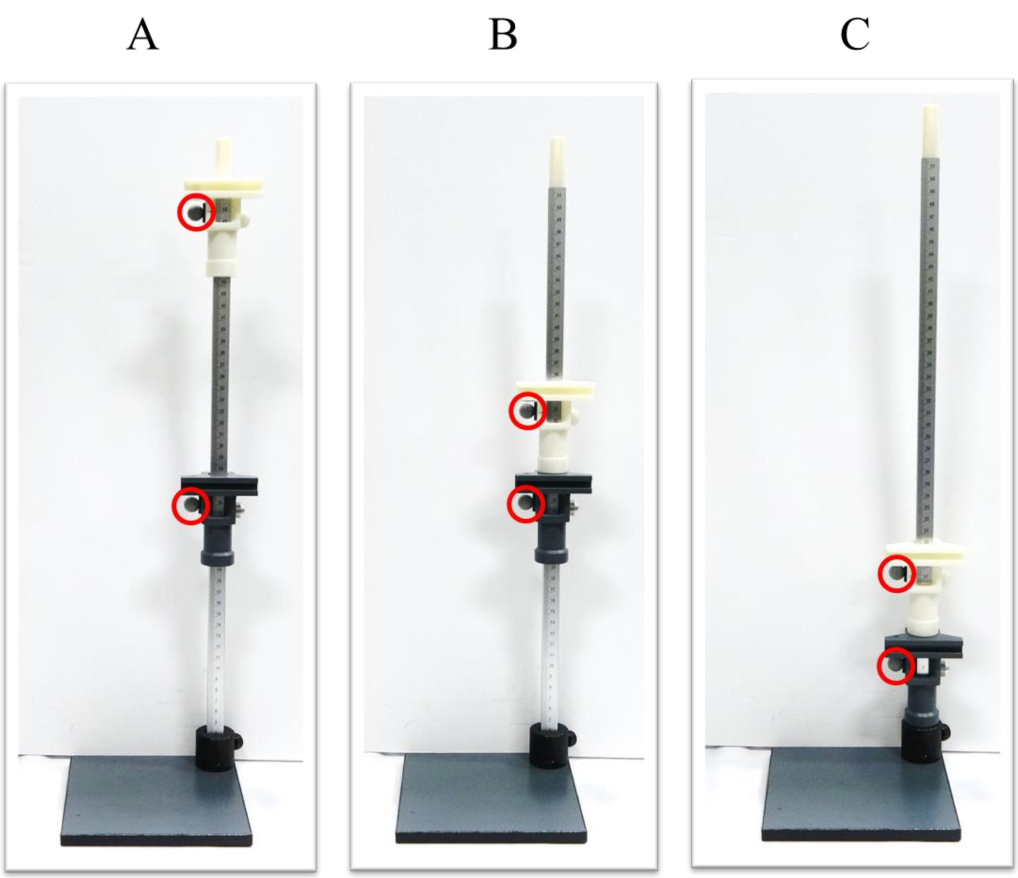

Figure 4. Stadiometer measuring branch holders with attached markers (circled in red) as used in the stadiometer fixture captures. (A) The starting position of the measuring branch holders; (B) the point at which the top measuring branch holder meets the bottom; and (C) the ending position of the measuring branch holders.

The two measuring branch holders were placed at 500 mm and 250 mm prior to starting each capture (Figure 4). During the capture, the top measuring branch holder was moved downward by a research team member until contacting the bottom measuring branch holder (Figure 4B). The two measuring branch holders were then moved together to the bottom of the stadiometer (Figure 4C). The measuring branch holders allow for an 80 mm space between the top and bottom markers while in contact. This resulted in a between-marker starting distance of 250 mm, a between-marker moving distance of 80 mm, and a between-marker ending distance of 80 mm. These captures were repeated with the stadiometer upright and at a 10-degree angle from vertical in the lateral direction. Each stadiometer position (straight or angled 10 degrees from the vertical) was captured twice for each TSB configuration (backless, upright back, upright back with brace, 15-degree back, and 15-degree back with brace), resulting in 20 total trials.

Human volunteer captures.

Human volunteer captures were conducted using two USAARL research team members, a female of approximately 35th percentile female height and a male of approximately 95th percentile male height, as defined by Gordon et al. (2014). The volunteers represent a range of anthropometries for testing marker positions, and both volunteered of their own volition. Volunteers were given spandex clothing to reduce the possibility of their regular clothing covering markers or affecting the tracking of the markers. Each volunteer had retroreflective markers placed along their spine at the first thoracic (T1), twelfth thoracic (T12), and sacrum (S1) vertebral levels (Figure 5). Triangular marker clusters were applied, positioning the apex of the triangle on the spinous process of the desired vertebrae and the other two markers placed to the left and the right of each main marker. Volunteer markers were composed of a flat plastic side with a diameter of 15 mm and a hemispherical semi-rigid plastic shell 5 mm tall. Each marker was covered with retroreflective marker tape to mimic a traditional motion capture marker. These markers allowed the volunteers to lean against the TSB without discomfort while also having a three-dimensional curved shape that can be tracked by the Vicon cameras. Positional data from the apex markers were used in the analysis. In the event of apex marker dropout, another marker from the respective cluster was substituted.

Figure 5. Retroreflective markers for the human volunteer capture sequences were placed at the T1, T12, and S1 vertebral levels. Circled markers are the apex markers of each cluster, the primary marker position used for analysis. While inertial measurement units are pictured, these data are not reported in this effort.

First, a neutral posture capture was taken for each TSB configuration prior to the torso movement captures. Volunteers were then asked to perform torso movements within all three planes during Vicon captures to observe if any visual distortion occurred while recording through the TSB. The specific movements included right and left lateral bending and forward flexion. The volunteer was instructed to begin and end each movement task in an upright, neutral posture. For lateral bending, the volunteer was asked to attempt to touch the floor to their right or left without rotating their torso and without lifting their thighs and buttocks up off the seat (Figure 6). Once they came to their maximum reach, they were asked to slowly return to the upright posture. During forward flexion captures, the volunteer was asked to bend their torso forward as if they were attempting to touch their toes (Figure 6). Once they came to their maximum reach, they were asked to slowly return to the upright posture. Each volunteer completed three trials of each torso movement across five different configurations of the TSB. The objective of the human movement captures was to determine the feasibility of tracking markers on moving people through the TSB and to establish lateral and forward limits of the current TSB design.

A B

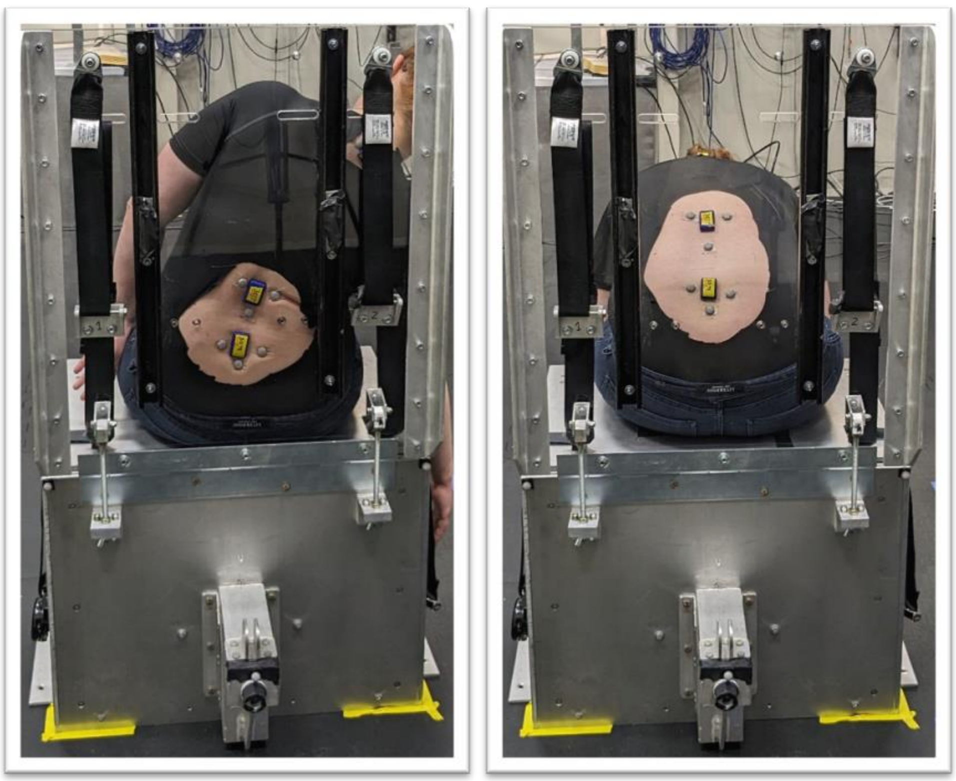

Figure 6. (A) Lateral bending and (B) forward flexion torso directional tasks performed during the human movement captures. While inertial measurement units are pictured, these data are not reported in this effort.

Analysis

Marker *x*-, *y*-, and *z*-positional data were exported from the Vicon system for analysis. The distances between retroreflective markers were calculated using the Euclidean distance formula derived from the Pythagorean theorem (Equation 1). Because spinal kinematic assessments require the quantification of relative motion, this was a priority measurement in the TSB feasibility evaluation.

$$Distance_{M1\rightarrow M2} = \sqrt[2]{(M2_X - M1_X)^2 + (M2_Y - M1_Y)^2 + (M2_Z - M1_Z)^2} \qquad \text{(Equation 1)}$$

Initial captures.

For the initial captures, the average marker positions for each capture were calculated. Distances between Markers 1 and 2 and between Markers 2 and 3 were computed from the average marker positions. Additionally, differences were calculated for between-marker distances in all data captures (Table 1). This allowed for comparisons of positions involving cameras from a variety of capture angles.

Stadiometer movement captures.

For the stadiometer movement captures, the distance between the top and bottom marker was computed for the entirety of the Vicon capture, except for where a marker became obscured or was dropped from tracking. A custom MATLAB program was used to identify three points from the capture: 1) movement start for the top marker; 2) movement start for the bottom marker; and 3) movement end for both markers (Figure 7). The segment prior to the top marker movement start was used in computing the between-marker starting distance. The segment during which both markers were moving was used to compute the between-marker moving distance. The segment after both markers stopped moving was used to compute the between-marker ending distance. The means and standard deviations (SDs) for the between-marker distances were computed for all three segments for each trial. The fixture was placed in an upright, vertical (straight) position (perpendicular to the seat pan) or angled at 10 degrees from vertical across the five TSB configurations. Two trials were conducted for each fixture orientation for all TSB configurations for a total of 20 trials.

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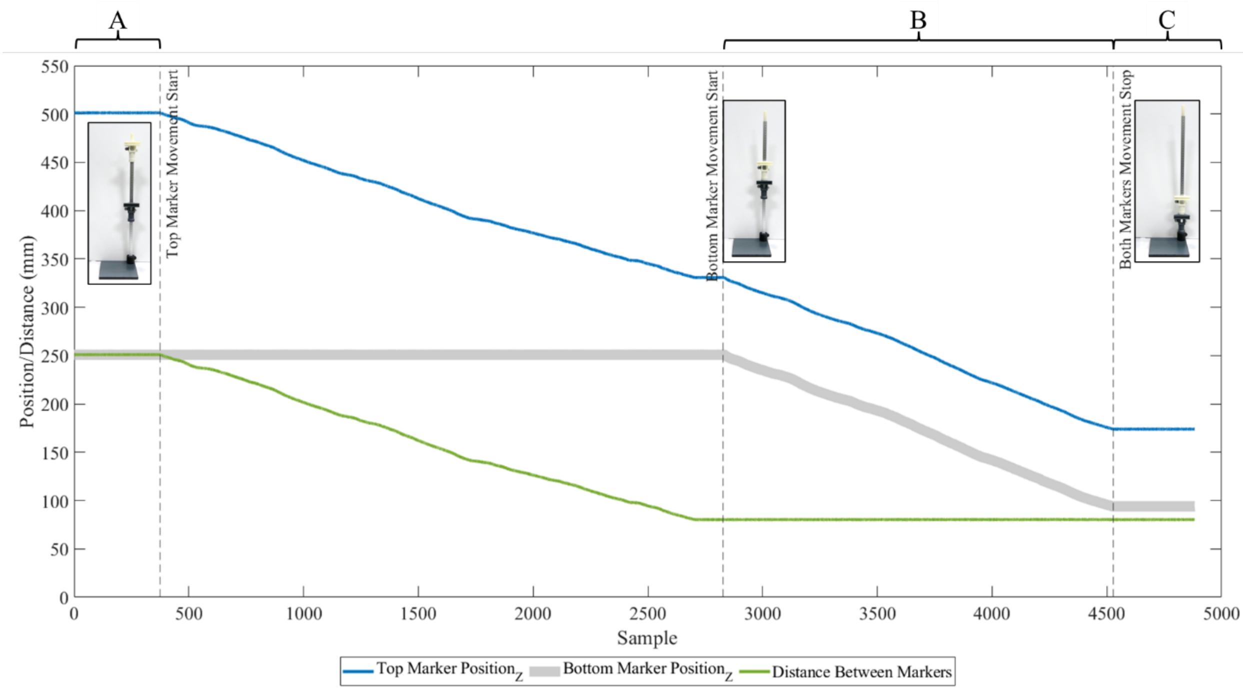

Figure 7. The top measuring branch holder marker *z*-axis positional data (blue), the bottom measuring branch holder *z*-axis positional data (gray), and the straight line between-marker distance (green) for stadiometer movement capture trials were plotted to allow the identification of marker movement segments. Segment A is the portion used to compute the between-marker starting distance. Segment B is the portion used to compute the between-marker moving distance. Segment C is the portion used to compute the between-marker ending distance. Also pictured are the stadiometer measuring branch holder positions during segment A, at the beginning of segment B, and during segment C.

Human movement captures.

For the human movement captures, a neutral posture trial was conducted for each TSB configuration prior to conducting lateral bending and forward flexion trials. Average distances were computed between the S1 and T12 markers and the T12 and T1 markers for the neutral posture trials. Additionally, S1 marker positions from the neutral posture trials were used to establish the starting position for lateral bending trials. In the lateral bending trials, the farthest left and farthest right positional marker data were reported for each vertebral level (S1, T12, and T1). In the forward flexion trials, starting positions were acquired from the participants' beginning and ending positions, then subtracted from the farthest forward positional marker data to determine the maximum forward distance from the TSB that could be detected at each vertebral level for each TSB configuration. These maximum positions provide a range of lateral and forward motions that can be tracked with the current motion capture arrangement and the TSB.

Results

Initial Captures

Initial captures, without human volunteers or a stadiometer, were conducted to measure the location of three retroreflective markers positioned on a rigid foam board (Figure 3) directly against the TSB. The average marker distances (in mm) between Markers 1 and 2 and between Markers 2 and 3 from different camera arrangements during the static captures were calculated (Table 2). Between-marker distances were calculated and averaged across the entire capture. The distances across the camera arrangements varied little; all averages differed by less than 1 mm from the average distance using all four cameras.

Table 2. Average Marker (M) Distances with All Cameras Compared to Individual Cameras Disabled

Distance	All cameras	Camera 1 disabled		Camera 2 disabled		Camera 3 disabled		Camera 4 disabled	
	Mean (mm)	Mean (mm)	MD (mm)	Mean (mm)	MD (mm)	Mean (mm)	MD (mm)	Mean (mm)	MD (mm)
M1-M2	285.29	285.38	0.09	284.98	0.32	285.36	0.06	285.85	0.56
M2-M3	222.70	222.75	0.05	222.26	0.44	222.74	0.04	222.95	0.25

Note. Mean difference (MD) is the difference between the mean distance value computed during the disabled camera trial and the mean distance value computed during the all cameras trial.

Stadiometer Movement Captures

The means and SDs of the distances between the two retroreflective markers for each stadiometer movement capture trial were calculated (Table 3). For each trial, distances between the two markers are reported for the starting distance between the markers (starting distance), the distance between the markers when both measuring branch holders were moving together (moving distance), and the final distance between the markers after movement (ending distance).

Actual starting, moving, and ending distances between the markers were 250 mm, 80 mm, and 80 mm, respectively, as measured using the stadiometer. The camera detection error of the starting distance between markers was within 2.5 mm of the actual distance for all TSB configurations in both the straight and angled stadiometer configurations. The average starting distance between markers of all configurations and trials was 250.99 mm (250 mm actual distance). The camera detection error of the moving distance between markers was within 1.5 mm of the actual distance for all TSB configurations in both the straight and angled stadiometer configurations. The average moving distance between markers of all configurations and trials was 80.50 mm (80 mm actual distance). The camera detection error of the ending distance between markers was within 0.5 mm of the actual distance for all TSB configurations and stadiometer configurations except for the upright back with brace TSB configuration when the stadiometer was angled (Table 3, third row from the bottom). In these trials, the error came within 1.66 mm of the actual distance. The average ending distance between markers for all configurations and trials was 80.27 mm (80 mm actual distance).

Table 3. Fixture Captures Between-Marker Distance Means and SDs

Stadiometer configuration		**TSB configuration**	**Trial 1**		**Trial 2**	
			Mean (mm)	**SD (mm)**	**Mean (mm)**	**SD (mm)**
Starting distance	**Straight**	backless	250.98	0.01	250.91	0.01
		upright back	251.29	0.02	251.11	0.03
		upright back with brace	252.34	0.05	252.39	0.03
		15-degree back	250.23	0.03	250.10	0.19
		15-degree back with brace	249.68	0.06	249.74	0.48
	Angled	backless	250.72	0.01	250.88	0.01
		upright back	250.83	0.02	250.72	0.01
		upright back with brace	250.49	0.03	250.37	0.01
		15-degree back	252.30	0.02	252.00	0.13
		15-degree back with brace	251.59	0.06	251.19	0.06
Moving distance	**Straight**	backless	80.36	0.04	80.37	0.04
		upright back	80.33	0.29	80.34	0.33
		upright back with brace	80.49	1.77	80.21	1.55
		15-degree back	79.72	0.56	79.80	0.55
		15-degree back with brace	80.70	0.70	80.66	0.65
	Angled	backless	80.27	0.04	80.28	0.04
		upright back	80.31	0.21	80.31	0.19
		upright back with brace	81.26	1.79	81.34	1.90
		15-degree back	80.39	0.52	80.41	0.50
		15-degree back with brace	81.11	0.79	81.35	0.74
Ending distance	**Straight**	backless	80.33	0.01	80.33	0.01
		upright back	80.35	0.02	80.35	0.01
		upright back with brace	79.96	0.02	79.99	0.02
		15-degree back	80.35	0.02	80.34	0.02
		15-degree back with brace	79.77	0.03	79.76	0.04
	Angled	backless	80.28	0.01	80.29	0.01
		upright back	80.35	0.01	80.36	0.02
		upright back with brace	81.66	0.02	81.66	0.02
		15-degree back	80.08	0.02	79.99	0.33
		15-degree back with brace	79.54	0.32	79.64	0.12

Human Volunteer Captures

Neutral posture captures.

Data collected from both volunteers in the neutral posture are shown in Table 4, which includes the average straight line distances between the T1 marker and the T12 marker, as well as the average straight line distances between the T12 marker and the S1 marker. Averages were computed from a single neutral posture capture for each volunteer in each TSB configuration. The distances between the markers could be captured through all TSB configurations. The distances between the T1 and T12 markers varied by a range of 16.22 mm and 21.74 mm for the 35th percentile female and 95th percentile male, respectively. The distances between the T12 and S1 markers varied by a range of 20.45 mm and 6.09 mm for the 35th percentile female and 95th percentile male, respectively.

Table 4. Average Distances Across Thoracic Spine and Lumbar Spine During Neutral Posture Volunteer Captures

Volunteer	**TSB configuration**	**T1-T12 distance (mm)**	**T12-S1 distance (mm)**
35th percentile female	backless	281.86	108.92
	upright back	276.22	101.31
	upright back with brace	278.24	114.35
	15-degree back	273.78	94.83
	15-degree back with brace	265.64	93.90
95th percentile male	backless	373.78	98.15
	upright back	372.01	97.14
	upright back with brace	375.39	102.65
	15-degree back	353.65	100.30
	15-degree back with brace	367.81	96.56

Torso movement captures.

The maximum average left and right lateral bending limits of the marker positions for both volunteers for T1, T12, and S1 were calculated from three trials per TSB configuration (Table 5). The SDs of these positions were also calculated. For the 35th percentile female, left and right maximum positions for the T1, T12, and S1 markers varied by approximately 86 mm, 24 mm, and 17 mm, respectively, across TSB configurations. For the 95th percentile male, left and right maximum positions for the T1, T12, and S1 markers varied by approximately 59 mm, 23 mm, and 20 mm, respectively.

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Table 5. Mean and SD of Maximum Left and Right Lateral Bending Positions Measured During Torso Movement

Marker position		TSB configuration	35th percentile female		95th percentile male	
			Mean (mm)	SD (mm)	Mean (mm)	SD (mm)
T1	**Left max**	backless	276.81	27.11	213.05	16.42
		upright back	196.30	6.21	220.71	39.92
		upright back with brace	190.58	7.26	245.67	2.16
		15-degree back	204.65	3.21	240.02	5.02
		15-degree back with brace	207.65	5.62	236.59	31.91
	Right max	backless	282.74	20.78	186.71	37.82
		upright back	209.64	8.94	147.39	22.71
		upright back with brace	199.19	15.31	206.76	18.93
		15-degree back	210.41	3.98	185.21	10.61
		15-degree back with brace	211.91	3.57	189.73	32.51
T12	**Left max**	backless	40.86	17.07	24.66	3.60
		upright back	23.37	3.82	30.89	13.50
		upright back with brace	27.75	9.14	35.29	5.85
		15-degree back	17.00	5.48	26.83	4.28
		15-degree back with brace	26.40	16.33	12.73	34.32
	Right max	backless	43.51	9.66	17.81	12.52
		upright back	26.45	3.70	7.45	4.31
		upright back with brace	41.19	3.70	18.60	2.19
		15-degree back	21.83	3.11	10.36	7.30
		15-degree back with brace	30.49	3.04	22.20	35.82
S1	**Left max**	backless	17.38	9.51	8.81	0.80
		upright back	0.80	0.34	11.76	6.62
		upright back with brace	8.29	4.21	9.30	2.87
		15-degree back	0.58	0.41	8.58	0.95
		15-degree back with brace	4.01	1.00	28.96	35.33
	Right max	backless	16.78	4.49	9.14	5.86
		upright back	0.55	0.21	6.35	1.75
		upright back with brace	13.22	1.15	10.30	0.47
		15-degree back	1.16	0.82	3.95	3.62
		15-degree back with brace	5.21	6.26	4.57	3.53

The average position of the markers for the maximum point of forward flexion of both volunteers for T1, T12, and S1 was calculated from three trials per TSB configuration (Table 6). The SDs of these positions were also calculated. More variability was observed in the forward maximum positions than in the left and right maximum positions (Table 5). For the 35th percentile female, forward maximum positions for the T1, T12, and S1 markers varied by approximately 242 mm, 91 mm, and 37 mm, respectively, across TSB configurations. For the 95th percentile male, forward maximum positions for the T1, T12, and S1 markers varied by approximately 239 mm, 58 mm, and 113.76 mm, respectively. Additionally, large standard deviations were noted for the 35th percentile female and are worthy of further investigation.

Table 6. Mean and SD of Maximum Positioning During Forward Flexion

Marker position	TSB configuration	35th percentile female		95th percentile male	
		Mean (mm)	SD (mm)	Mean (mm)	SD (mm)
T1	backless	384.24	77.98	502.95	2.05
	upright back	364.62	172.96	435.32	14.24
	upright back with brace	352.15	71.94	427.02	4.57
	15-degree back	519.65	150.34	662.05	22.16
	15-degree back with brace	594.35	56.74	665.85	1.37
T12	backless	193.09	5.72	246.50	8.65
	upright back	187.20	9.22	243.80	19.10
	upright back with brace	166.19	53.08	232.74	11.30
	15-degree back	256.87	8.88	290.77	1.59
	15-degree back with brace	239.97	6.40	284.17	11.96
S1	backless	113.05	3.26	131.46	5.63
	upright back	95.16	5.33	134.64	12.73
	upright back with brace	106.27	3.50	79.08	5.01
	15-degree back	132.04	4.92	192.84	12.96
	15-degree back with brace	120.89	3.47	172.03	31.36

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Discussion

The results indicate that regardless of TSB configuration, the retroreflective markers can be tracked with minimal error or distortion for the ranges of movement expected from volunteers on the MARS. Safety protocols for the MARS require occupants to be restrained using the chair's five-point restraint during all MARS operations, which limits the available lateral and forward motion for participants. Additional considerations will still need to be given regarding camera placement and the number of cameras to be used to limit marker dropout around the various support structures of the MARS chair.

Initial Captures

The initial captures were conducted to determine if a change in marker positional data would occur due to refraction or other optical distortion as the motion capture cameras were all positioned at different angles from the TSB. During the initial captures with the markers placed on a rigid foam board, three of the four Vicon motion capture cameras tracked the marker distances through the TSB with less than one mm difference from the distance captured by all four cameras. This indicates that even with fewer cameras at different angles, it is possible for the cameras to effectively determine non-moving (stationary) marker position through the TSB with minimal distortion.

Stadiometer Movement Captures

The fixture capture trials indicate that regardless of the configuration of the TSB (e.g., upright back, upright back with brace, 15-degree back, or 15-degree back with brace) or the angle of the stadiometer (no angle or 10-degree angle), the motion capture cameras can track marker positions very well while static or in motion through the TSB. Marker distance errors were within 2.5 mm, 1.5 mm, and 1.7 mm of the actual marker distances for starting distance (250 mm), moving distance (80 mm), and ending distance (80 mm), respectively. There were some tracking issues seen when the TSB brace was mounted. As the fixture markers moved through the region behind the TSB brace, the camera view of the markers was blocked, and some marker dropout occurred. Even so, when the markers could be seen around the brace, the positioning was very close to what was measured with a maximum error of 1.35 mm for the moving distance trials in which the brace was applied (moving distance, angled stadiometer, 15-degree back with brace; Table 3). Only four motion capture cameras were used for this proof-of-concept test. It is likely that with more cameras, the positions of the markers can be tracked through more samples with less dropout.

Human Volunteer Captures

The retroreflective markers along the spine of a 35th percentile female and a 95th percentile male (both in height) could be tracked by the motion capture cameras through all configurations of the TSB. Compared to the initial and stadiometer movement captures, higher variances and SDs were seen for the human movement captures. These are likely due to a larger variety in the volunteers' initial positioning and movement, as well as difficulty in the cameras tracking markers through increased ranges of motion. As the volunteers completed the torso movements, marker obstructions were largely due to either markers being blocked by support structures on the TSB (Figure 6A) or the volunteer moving out of the field of view of the camera setup. This issue had a larger impact for the 35th percentile female as her stature allowed the markers to become obscured sooner and resulted in higher standard deviations than the 95th percentile male (Table 6). These observations were not anticipated by the research team, as the original concern of this effort was the presence of an optical distortion affecting motion capture through the TSB itself. However, marker obfuscation issues are likely to be easily remediated through the use of additional motion capture cameras and refined camera positioning.

Neutral posture captures.

Between-marker distances for the neutral posture captures had a maximum difference of 21.74 mm (upright back with brace and 15-degree back, 95th percentile male, T1 to T12 distance; Table 4). As markers had a diameter of 15 mm, this is a maximum variance of less than 1.5 marker widths. While the variance is larger than desired, this is still a relatively small error amount that could likely be remedied by increasing the number of cameras used to decrease the opportunity for marker dropout behind TSB structures.

Torso movement captures.

During lateral bending, the TSB support and restraint structures, in addition to the previously mentioned cross-brace, all contributed to marker dropout. Complete ranges of position for S1 and T12 markers were collected, but the T1 marker became obstructed as the volunteers approached the extremes of lateral motion. An example of the T1 marker obstruction can be seen in Figure 6A. Despite this, all TSB configurations allowed for a successful capture window width of more than 350 mm from the left maximum to the right maximum recorded values of the T1 marker, with the narrowest lateral range at approximately 368 mm (upright back, 95th percentile male; Table 5). This range is adequate for protocols involving volunteers in a seated position on the MARS, as seating restraints will always be in use, which will restrict volunteer lateral motion within these limits. In forward flexion trials, the largest forward maximum positions were recorded during a configuration when the TSB was in place, as opposed to the backless configuration (Table 6). This indicates marker dropout likely occurred from variables other than the seating structures alone. The markers used for human volunteer captures in this effort have a flat plastic side approximately 15 mm in diameter and a hemi-spherical shell that is approximately 5 mm tall. These markers allowed for the volunteers to sit against the TSB without discomfort; however, they become difficult to track when the surface they are attached to begins to rotate away from the motion capture cameras. During the forward flexion trials, the volunteers rotated forward, away from the motion capture cameras, all of which were located on a wall approximately 2387.6 mm to the rear of the TSB. These contributors to marker dropout (TSB support structures, marker geometry, camera positioning) compounded for the 35th percentile female to a greater degree as her stature caused the markers to rotate away and become obstructed sooner than for the 95th percentile male. Although these issues complicated the data collection for the maximum forward positions, all TSB configurations allowed for a successful capture window depth of more than 350 mm, 160 mm, and 70 mm for the T1, T12, and S1 markers, respectively (Table 6). Similar to the lateral limits, this limit in flexion distance is considered acceptable for MARS protocols since the use of chair restraints limits the volunteers’ forward motion within this distance.

Limitations

The methods developed in this report can be used for future spinal transmissibility studies involving the MARS; however, certain limitations still exist. At this time, the TSB has only been studied in stationary chair conditions (i.e., the MARS was not operated). While an evaluation of the TSB in dynamic conditions (i.e., with the MARS on) is still needed, this test demonstrates that the material properties of the TSB are suitable for the collection of motion capture data.

The TSB support structures can obscure markers from the sight of the motion capture cameras. Using additional cameras could decrease, but may not fully eliminate, marker dropout for various volunteer anthropometries. A redesign of the seat back support structures may be required to fully capture seated spinal kinematics. The results presented here indicate that four cameras can satisfactorily track motion through the TSB; however, additional cameras would provide an increased range of detectable motion around and beyond the TSB.

While configuring and troubleshooting the capture space, the research team discovered the infrared strobe used by the motion capture cameras could reflect off the TSB, creating interference in the motion capture cameras. Accounting for this reflective interference could create a limitation in the positioning of motion capture cameras relative to the TSB. Additionally, volunteers used in this effort were not wearing any type of body armor even though it is common for Service Members to do so in operational environments. Future studies examining spinal kinematics in military environments will have additional complications to resolve if volunteers are required to wear body armor.

Despite these limitations, the work presented here is a critical step forward for the collection and evaluation of seated spinal kinematics in operationally-relevant WBV exposures. Motion capture data collection was facilitated by the TSB and the TSB will allow researchers to deliver valuable information to stakeholders during future research efforts aimed at determining the health effects of WBV.

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Recommendations

The TSB can be used in future research efforts to characterize seated spinal kinematics. Based on the findings of the present study, future research should focus on, and/or include the following:

- Use additional cameras for enhanced views and controlled positioning of cameras such that they are not exactly perpendicular to the area of interest to reduce the infrared strobe reflection off the surface of the TSB.
- To assist with the first recommendation and reduce marker dropout from TSB support structures, use modified camera angles to have a smaller lateral angle to the TSB to allow slightly downward and slightly upward views of the spine.
- Use the MARS to introduce motion (vibration), including sine dwell and replication of both military ground vehicle and air ride signatures. It is not yet known how the dynamic movement of the chair will affect the ability of the Vicon motion capture camera system to track the retroreflective markers through the TSB chair. Additionally, contact of the TSB with the retroreflective markers may induce motion artifacts, causing movement of the markers separate from vertebra motion and complicating motion capture data collection.
- Use helmet systems and simulated body armor while testing on the MARS. Service Members often wear additional equipment that could affect the spinal kinematic response to whole-body vibration.

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Conclusion

This effort was a proof-of-concept test to assess the feasibility of capturing spinal kinematic data through a TSB chair designed for the MARS. In stationary chair capture configurations, the TSB performed very well when tracking retroreflective markers using Vicon motion capture cameras. The TSB will expand the capabilities of current USAARL musculoskeletal and vibration research by allowing the capture and quantification of whole spine spinal kinematics in seated WBV research. This capability will contribute to future research and modeling efforts targeted at assessing injury risk and mitigation strategies in dynamic military environments. Future considerations to improve capturing spinal kinematics through the TSB chair include the following: mounting and testing the chair on the MARS; adding more motion capture cameras angled toward the back of the chair; redesigning the seat back brace; and creating a methodology for capturing spinal kinematics with the presence of additional equipment (e.g., body armor, helmet systems, restraint systems).

References

Alem, N. M., Meyer, M. D., & Albano, J. P. (1995). *Effects of head supported devices on pilot performance during simulated helicopter rides* (Report No. 95-37). U.S. Army Aeromedical Research Laboratory.

Alem, N., Hiltz, E., Breaux-Sims, A., & Bumgardner, B. (2004, November). *A new methodology for health hazard assessment of repeated shock in military tactical ground vehicles* [Poster presentation]. In 24th Army Science Conference, Orlando, Florida. Paper No. KP-15.

Alem, N. (2005). Application of the new ISO 2631-5 to health hazard assessment of repeated shocks in U.S. Army vehicles. *Industrial Health*, *43*(3), 403–412. https://doi.org/10.2486/indhealth.43.403

Andersen, K., Baardsen, R., Dalen, I., & Larsen, J. P. (2015). Recurrent and transient spinal pain among commercial helicopter pilots. *Aerospace Medicine and Human Performance, 86*(11), 962–969. https://doi.org/10.3357/AMHP.4237.2015

Baig, H. A., Dorman, D. B., Bulka, B. A., Shivers, B. L., Chancey, V. C., & Winkelstein, B. A. (2014). Characterization of the frequency and muscle responses of the lumbar and thoracic spines of seated volunteers during sinusoidal whole body vibration. *Journal of Biomechanical Engineering*, *136*(10), 101002.

Barazanji, K. W., Alem, N. M., Dodson, J., Erickson, B., Guerrero, R., & Reyes, S. (1998, October 19-21). *Effects of head-supported devices on female aviators during simulated helicopter rides* [Paper presentation]. Research and Technology Organization Human Factors and Medicine Panel Symposium, San Diego, CA, United States.

Barazanji, K. W., & Alem, N. M. (2000). *Effects of head-supported devices on female aviators during simulated helicopter rides part I: Biomechanical response* (Report No. 2000-16). U.S. Army Aeromedical Research Laboratory. https://apps.dtic.mil/sti/citations/ADA386456

Bovenzi, M., & Hulshof, C. T. J. (1998). An updated review of epidemiological studies on the relationship to whole-body vibration and low back pain. *Journal of Sound and Vibration, 215*(4), 595–611. DOI:10.1006/jsvi.1998.1598

Butler, B. P. (1992). *Helmeted head and neck dynamics under whole-body vibration.* [Doctoral dissertation, University of Michigan]. Deep Blue. https://www.proquest.com/docview/303980432

Butler, B. P., & Alem, N. M. (1997). *Long-duration exposure criteria for head-supported mass* (Report No. 97-34). U.S. Army Aeromedical Research Laboratory. https://apps.dtic.mil/sti/tr/pdf/ADA329484.pdf

Cameron, B., Morrison, J., Robinson, D., Roddan, G., & Springer, M. (1998). *Development of a standard for the health hazard assessment of mechanical shock and repeated impact in army vehicles final report—Summary of phases 1-5* (Report No. 96-1). U.S. Army Aeromedical Research Laboratory.

Chancey, V. C., Bumgardner, B. A., Turner, D. D., Breaux-Sims, A. M., Flowers, G. T., & Beale, D. G. (2007). A priori motion profile control and dynamic performance of the Multi-Axis Ride Simulator (MARS) facility. *Proceedings of ASME 2007 International Mechanical Engineering Congress and Exposition*, IMECE2007-42122, 11-15 November 2007, Seattle, WA. https://doi.org/10.1115/IMECE2007-42122

De Oliveira, C. G., & Nadal, J. (2005). Transmissibility of helicopter vibration in spines of pilots in flight. *Aviation, Space, and Environmental Medicine, 76*(6), 576–580. https://www.researchgate.net/publication/7797822_Transmissibility_of_helicopter_vibration_in_the_spines_of_pilots_in_flight

Dupuis, H., & Zerlett, G. (1987). Whole-body vibration and disorders of the spine. *International Archives of Occupational and Environmental Health, 59,* 323–336. https://doi.org/10.1007/BF00405276

Gordon, C. C., Blackwell, C. L., Bradtmiller, B., Parham, J. L., Barrientos, P., Paquette, S. P., Corner, B. D., Carson, J. M., Venezia, J. C., Rockwell, B. M., Mucher, M., & Kristensen, S. (2014). *2012 anthropometric survey of U.S. Army personnel methods and summary statistics* (Report No. NATICK/TR-15/007). Army Natick Soldier Research, Development and Engineering Center. https://dacowits.defense.gov/LinkClick.aspx?fileticket=EbsKcm6A10U%3D&port alid=48

Griffin, M. J. (1996). Whole-body biodynamics. In *Handbook of human vibration* (1st ed., pp. 333–385). Academic Press. https://shop.elsevier.com/books/handbook-of-human-vibration/griffin/978-0-12-303041-2

Harrer, K. L., Yniguez, D., Majar, M., Ellenbecker, D., Estrada, N., & Geiger, M. (2005). Whole body vibration exposure for MH-60S pilots. *Proceedings of 43rd SAFE Association Symposium*, 24-26 October, Salt Lake City, UT.

International Standards Organization. (2004). *Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration—Part 5: Method for evaluation of vibration containing multiple shocks* (ISO 2631-5:2004[E]). https://www.iso.org/standard/35595.html

Knox, J. B., Deal, J. B., Jr, & Knox, J. A. (2018). Lumbar disc herniation in military helicopter pilots vs. matched controls. *Aerospace Medicine and Human Performance, 89*(5), 442–445. https://doi.org/10.3357/AMHP.4935.2018

Landau, D. A., Chapnick, L., Yoffe, N., Azaria, B., Goldstein, L., & Atar, E. (2006). Cervical and lumbar MRI findings in aviators as a function of aircraft type. *Aviation, Space, and Environmental Medicine*, *77*(11), 1158–1161. https://www.ingentaconnect.com/content/asma/asem/2006/00000077/00000011/art00010;jsessionid=150rjwqbyytj0.x-ic-live-02

Mansfield, N. J., & Griffin, M. J. (2000). Non-linearities in apparent mass and transmissibility during exposure to whole-body vertical vibration. *Journal of Biomechanics, 33*, 933–941. https://doi.org/10.1016/S0021-9290(00)00052-X

Rhamatalla, S., Xia, T., Contratto, M., Kopp, G., Wilder, D., Law, L. F., & Ankrum, J. (2008). Three-dimensional motion capture protocol for seated operator in whole body vibration. *International Journal of Industrial Ergonomics*, *38*, 425–433. https://doi.org/10.1016/j.ergon.2007.08.015

Rozali, A., Rampal, K. G., Shamsul Bahri, M. T., Sherina, M. S., Shamsul Azhar, S., Khairuddin, H., & Sulaiman, A. (2009). Low back pain and association with whole body vibration among military armoured vehicle drivers in Malaysia. *The Medical Journal of Malaysia*, *64*(3), 197–204. http://www.e-mjm.org/2009/v64n3/low_back_pain.pdf

Seroussi, R. E., Wilder, D. G., & Pope, M. H. (1989). Trunk muscle electromyography and whole body vibration. *Journal of Biomechanics*, *22*(3), 219–229.

Village, J., Roddan, G., Remedios, B., Morrison, J., Rylands, J., Brown, D., Robinson, D., Cameron, B., & Butler, B. (1995). *Development of a standard for the health hazard assessment of mechanical shock and repeated impact in Army vehicles: Phase 3-pilot tests* (Report No. CR 95-3). U.S. Army Aeromedical Research Laboratory.

Wang, W., Rakheja, S., & Boileau, P. É. (2006). Effect of back support condition on seat to head transmissibilities of seated occupants under vertical vibration. *Journal of Low Frequency Noise, Vibration and Active Control*, *25*(4), 239–259. https://journals.sagepub.com/doi/pdf/10.1260/026309206779884874

Appendix A. Acronyms and Abbreviations

GPa	Gigapascals
Hz	Hertz
ISO	International Standards Organization
LBP	Lower back pain
M	Marker
MARS	Multi-Axis Ride Simulator
MD	Mean Difference
mm	Millimeter
MOS	Military occupational specialty
MRAP	Mine-Resistant Ambush Protected (vehicle)
SD	Standard deviation
SM	Service Member
TSB	Transparent seat back
UH-60	Black Hawk helicopter
USAARL	U.S. Army Aeromedical Research Laboratory
WBV	Whole-body vibration

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