

Balance Maintenance during Seated Reaches of People with Spinal Cord Injury

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ABSTRACT

In many task analyses using digital human figure models, only the terminal or apparently most stressful posture is analyzed. For reaches from a seated position, this is generally the posture with the hand or hands at the target. However, depending on the characteristics of the tasks and the people performing them, analyzing only the terminal posture could be misleading. This possibility was examined using data from a study of the reaching behavior of people with spinal cord injury. Participants performed two-handed forward reaching tasks. These reaches were to three targets located in the sagittal plane. The terminal postures did not differ significantly between those with spinal cord injury and those without. However, motion analysis demonstrated that they employed distinct strategies, particularly in the initial phase of motion. The location of the center of pressure throughout each motion was calculated using inverse dynamics and was found to be a good indicator of the strategies employed and the behavior differences between the two groups.

INTRODUCTION

Design of seated work environments, including those for people with spinal cord injury, requires a quantification of worker needs and limitations. When analyzing a task using a digital human figure model, manikins are frequently posed in a terminal posture that reflects anticipated extremes in loading or joint range of motion. This analysis may not be sufficient to identify potentially stressful tasks across populations with different movement capability.

Previous research has indicated differences in muscle recruitment and motor behavior in people with spinal cord injury (SCI) and those without. Seelen et al. (2001) and Potten et al. (1999) measured electromyographic levels in various muscles and found that people with SCI recruited different muscle groups to complete similar tasks. Other differences include a reduced ability to

move the center of pressure (COP) forward in the sagittal plane without losing balance (Seelen et al., 1998).

In the present study, two groups of participants (SCI and a control group) performed six material handling tasks in the sagittal plane. The motions and terminal postures were compared between the groups.

METHODS

Participants

The experiment was conducted within the Human Motion Simulation (HUMOSIM) Laboratory at the University of Michigan. Nine participants with spinal cord injury (SCI) were recruited for the study. Nine participants without SCI were selected to match range of seated height of the SCI group. Each of the SCI participants had complete lesions on their spinal cord in either the thoracic or lumbar regions. Injury level ranged from T4 to L4. All study procedures were approved by an appropriately constituted institutional review board at the University of Michigan. Participants were compensated for their time.

Procedure

Detailed information about the data collection and processing procedures is available in Chaffin et al. (2004) and Chaffin (2001). Only a portion of the data collected is presented in this paper. An outline of relevant equipment and procedures is given below.

Participants were first informed of the study objectives and procedures. Following written consent, demographic and anthropometric measures were taken. Participants then performed a series of maximum voluntary contraction (MVC) tests to determine strength for several types of exertion. Retroreflective markers used for optical motion tracking (MacReflex system) were placed on anatomical landmarks. Six sensors from the Flock of

Birds (Ascension Technologies) tracking system were also placed on the subjects. Joint center locations for the torso, head, and upper extremities were calculated from the data obtained using the two systems.

During motion trials, participants reached with both hands to one of three shelf locations located in the sagittal plane 74 cm in front of the seat H-point (a reference point approximating the hip location of a midsize male) and 16 cm, 49 cm, and 87 cm above it (Figure 1). Trials were evenly split between moving a weighted crate out to the designated shelf and moving empty-handed to retrieve a crate. The mass of the crate was selected to be 25% of the one-hand extended-arm shoulder strength determined earlier. Contact switches at the home location and on the shelves were used to define the start and end of the motion. All trials were performed in a seat designed to simulate a wheelchair (Figure 1) and allow participants with SCI to transfer easily. Those with SCI were also fitted with a harness that was attached to the back of the test fixture to prevent injury in the event of a loss of balance.

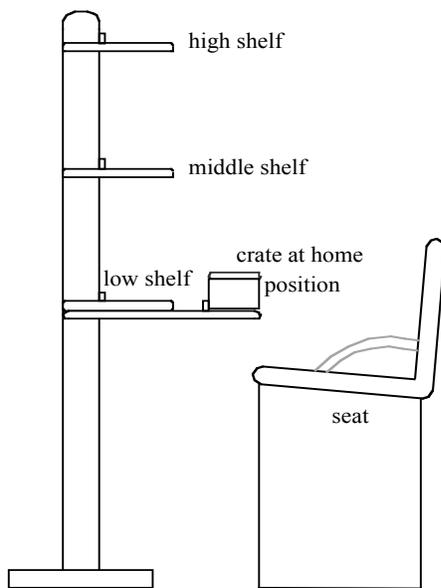


Figure 1. The testing apparatus, including the three shelves used for this study and the crate that participants moved.

Each trial wherein a crate was placed on a particular shelf was followed by a trial where the participant moved from the home location back to the shelf to retrieve the crate. At least two and as many as four sets of motions were attempted for each shelf and the order of presentation was randomized.

Data Analysis

The motions from each trial were recorded and processed. The terminal posture, as indicated by the torso and elbow angles, was determined for each trial. Additionally, the average angular velocity of the torso during the latter part of the reach trial was calculated.

Statistical analysis was performed using the JMP software (SAS Institute).

A Newton-Euler inverse dynamics (NEID) program developed for the analysis of seated and standing reach tasks was used to calculate the dynamic joint forces and torques throughout the motion. Inertial properties for the body segments were calculated from segment lengths using the relationships given by de Leva (1996). Using the external joint forces and torques predicted by the NEID analysis, the location of the center of pressure (COP) under the sitter's body was determined at 25 Hz throughout the motion.

RESULTS

Terminal Posture

Figure 2 shows torso and elbow angles in the terminal posture for the SCI and control (non-SCI) groups. The torso angle is defined as the side-view angle of a line from the L5/S1 joint to C7/T1 joint with respect to vertical, positive forward of vertical. Elbow angle is the flexion of the elbow relative to fully extended; larger values indicate more elbow flexion. Analysis of variance and post-hoc contrasts showed significant differences in the mean values of these measures only for the elbow angle at the middle shelf height. For this condition, the elbow flexion for the SCI group averaged 8.4 degrees less than for the control group, indicating that the participants with SCI completed reaches to the middle shelf with a straighter elbow posture. The effect of the weight in the hands for reaches to the middle shelf did not differ significantly between the groups, but elbow flexion in the terminal posture was six degrees greater when delivering the crate than when reaching to pick it up. This is consistent with a desire to reduce the shoulder moment due to the weight by keeping the weight closer to the body. From a geometric perspective, the more-flexed elbow posture might be expected to be accompanied by greater torso angle (forward lean), but the effect was not significant in the data.

Movement Duration

Participants with SCI took longer to complete the loaded reaches (average across shelves of 3.3 s vs. 3.1 s, $p < 0.01$). The time required to complete the loaded reaches averaged 3.0, 3.1, and 3.5 s for the low, middle, and high shelves respectively. The movement durations for the low and middle shelves were not significantly different, but the time required for delivering the crate to the high shelf was significantly greater than for the other shelves ($p < 0.001$). The interaction between group and shelf position was not significant. The timing data for the unloaded reaches were not analyzed because of difficulty in determining when the participant reached the target with both hands.

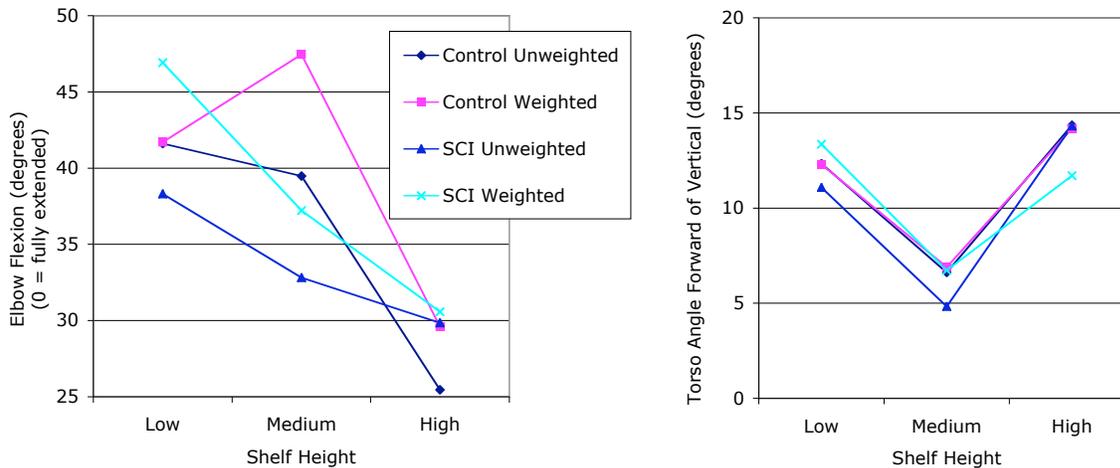


Figure 2. Mean elbow flexion and torso angle forward of vertical for the control and SCI groups as a function of shelf height. In weighted reaches, participants held a crate in both hands and delivered to the shelf. In unweighted reaches, participants reached empty handed for the crate on the shelf.

Inverse Dynamics and Movement Patterns

Joint forces and torques were calculated using the NEID and the observed torso and upper extremity kinematics. The forces and moments calculated for the L5/S1 joint were used to calculate the effective center of pressure by determining the location at which the calculated vertical force would need to be applied to produce the calculated moment. For the current sagittal plane analysis, only the fore-aft position of the COP was analyzed. Figure 3 shows the fore-aft trajectory of the COP for loaded reaches to all three shelves.

As noted above, the movement duration was generally greater for participants with SCI. Considering all three shelves, the terminal COP excursion was greater for the SCI group (138 mm vs. 111 mm, $p=0.03$), although the plot makes clear that this difference is most notable for the lower shelf. Since the postures at the lower shelf were similar between the groups (see Figure 2), and the overall body dimensions were similar, this result is due to the fact that the COP started out more rearward relative to the L5/S1 joint for the SCI group than for the control group (2 mm forward of L5/S1 for the SCI group vs. 45 mm for the control group, $p<0.001$). This reflects a difference in seated torso orientation, with the SCI group sitting with slightly more reclined and more stable torso postures with the backrest is more fully engaged.

Figure 3 shows evidence of markedly different movement patterns for the two groups. The distinction is greatest for the low shelf, although it is also present in the data for the other shelves. The COP trajectories for the control group (dashed lines) show a smooth forward movement with gradual acceleration and deceleration. Since the COP is calculated from the low-back moment, this implies a steady, controlled application of low-back extension moment to first allow the torso to fall forward and then to gradually stop it as the hands reach the target.

In contrast, the COP excursion data from the SCI group show a more complicated movement pattern. Four of the nine participants with SCI produced kinematics that indicate a rearward shift of the COP during the first phase of the motion. The participants achieved this by pushing off as they lifted the weight, angling the torso rearward slightly, and shifting their heads rearward as they lifted the weight.

After this preparatory phase, the forward progression of the COP is then more rapid for the SCI group as they complete the reach. The COP excursions for the participants with SCI show oscillation and overshoot during the final 1.5 seconds of the reach, indicating a more complicated pattern of control.

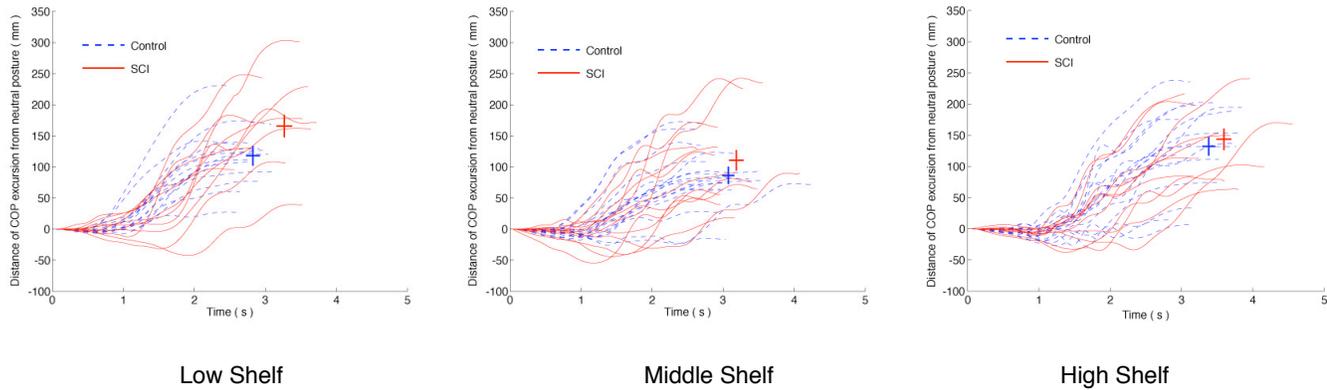


Figure 3. Forward excursion of the center of pressure calculated from the inverse dynamics model for weighted reaches to the top, middle, and low shelves. Crosses indicate the mean timing and COP excursion, ± 1 standard error, for the terminal posture.

DISCUSSION

The statistical analysis indicated no meaningful differences between the terminal postures of the two groups. As expected, the terminal postures were strongly affected by shelf location, indicating that the geometric interaction between the participant's body segment dimensions and the shelf location was the primary determinant of posture. An analysis of the terminal postures alone would conclude that the risk posed by the task with respect to shoulder and lower-back loading was similar.

However, the motions of the two participant groups were significantly different. The SCI participants took slightly longer to complete the same weighted tasks. The inverse dynamics analysis, which yielded plots of the COP excursion, provides insight into the movement patterns.

As Figure 4 shows, the motion of each group while moving the crate can be divided into two distinct phases: *preparatory* and *fall*. In the preparatory phase, participants lift the crate and make torso posture changes to maintain balance without beginning the forward motion. Those with SCI required additional time in this phase as they stabilized themselves before beginning the motion to the target. In the fall phase, participants fell towards the target and caught themselves as they placed the crate on the shelf. Using this strategy, those with SCI were able to greatly exceed the 5 cm forward COP excursion limit found by Seelen, et al. (1998). This “catching” procedure is likely responsible for the overshoot and retrograde motion of the COP observed at the end of the motions of the SCI group.

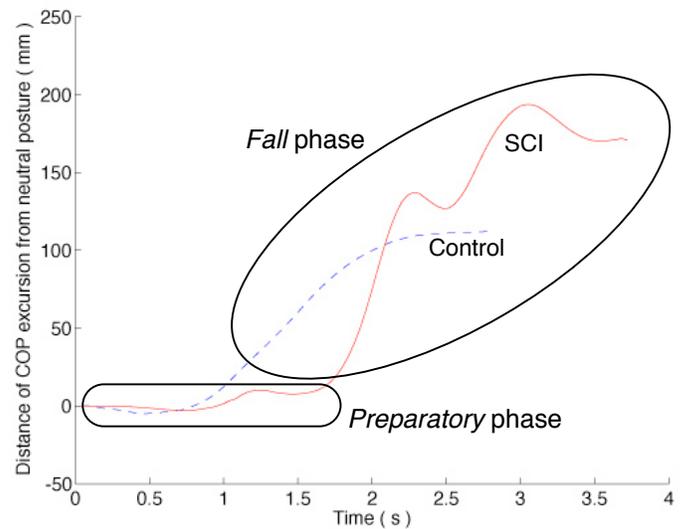


Figure 4. Sample forward COP excursion of participants from the SCI and control groups. The *preparatory* and *fall* motion phases are identified.

Although the participants with SCI took longer to complete the tasks, their motion in the fall phase was faster and the transition between the two phases less gradual. Even though both groups are falling into the targets, the control participants used their abdominal, back, and leg muscles to smoothly decelerate the torso as they neared the shelf. As expected, the participants with SCI were less successful in managing the fall phase, resulting in larger COP excursions and more rapid rate of COP excursion.

Seelen et al. (1998) showed that people with low- to mid-level SCI have longer motion times than people without due to increased complexity of the motor strategy. The current study demonstrates this additional movement complexity for weighted reaches. The COP excursion analysis reveals the manner in which people with SCI are able to increase their reach and object manipulation

capability by planning and executing a falling motion toward the target. Dickerson et al. (2004), using the dataset analyzed for this paper, showed that the more-rapid forward COP excursions observed with the SCI group are accompanied by higher levels of shoulder stress.

Together, these analyses emphasize the need to consider the entire movement when assessing work tasks. A static analysis of the terminal posture may not adequately detect high levels of stress, particularly across populations with different movement patterns.

ACKNOWLEDGMENTS

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