The effect of an on-body assistive device on transverse plane trunk coordination during a load carriage task

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Abstract
Load carriage is a physically demanding task that is often required of employees in many different occupations. The Mover’s Assistive Device (MAD) is an on-body ergonomic assistive device designed to help professional movers transfer boxes during two techniques of hand-held load carriage: anterior carriage and posterior carriage. The purpose of this study was to examine the intersegment coordination between the trunk and pelvis as well as the trunk and box, since coordination may be a mechanism to reduce the amount of stress exerted on the back during load carriage. Thirteen males completed a handheld load carriage task in a laboratory setting using two popular techniques employed by professional movers (anterior/posterior), with and without the assistance of the Mover’s Assistive Device (MAD); resulting in a total of four conditions. Triads of retro-reflective markers tracked the angular positions of the trunk, pelvis and the load being carried. Intersegment coordination between the trunk-pelvis and the box-trunk were measured using continuous relative phase angles in the transverse plane of motion. No trunk coordination differences were observed across carrying techniques (anterior/posterior); however, under all conditions users walked with a near in-phase coordination pattern, which is believed to help reduce the risk of injury. MAD use resulted in decreased perceived discomfort and more in-phase coordination between the trunk-pelvis, which may help reduce injury risk when carrying loads either anteriorly or posteriorly.

1. Introduction
Professional movers are required to transfer large quantities of objects between houses and moving trucks on a daily basis, and the moving industry has been classified as a high-risk occupation for the development of work-related musculoskeletal disorders (Silverstein et al., 2002). The transfer of boxes is a cause for concern because of the large quantities and the large range of sizes and weights. Biomechanical research with respect to load carriage during gait has primarily focused on load carriage when the load’s weight is predominantly carried by the trunk and hips, often in the form of a backpack (Fiolkowski et al., 2006; Knapik et al., 2004). However, backpack use is time-consuming and impractical in the moving industry (Kudryk, 2008). Experienced movers prefer to use the posterior carriage (PC) technique, because it improves visibility when traversing difficult terrain or obstacles, and feels less physically demanding than the anterior carriage (AC) technique (Kudryk, 2008).

In comparison to the AC technique, the PC technique results in significantly reduced muscular activity of the anterior deltoid and the thoracic and lumbar erector spinae muscles, but an increase in activity of the posterior deltoid muscles (Kudryk, 2008). Decreases in erector spinae muscular activity have also been observed when carrying a backpack versus a front pack (Motmans et al., 2006). It has been suggested that the PC technique may be beneficial to overall back health (Kudryk, 2008), since increased muscle contraction intensity can lead to increased magnitudes of muscle-induced spinal compression (McGill and Norman, 1986; Potvin et al., 1990; Dolan et al., 1999), which is a significant predictive factor for the development of low back pain (Norman et al., 1998). A Mover’s Assistive Device (MAD) was developed as an ergonomic load carriage aid to reduce task difficulty and increase comfort (Fig. 1) (Kudryk, 2008). Although the device did not alter erector spinae muscle activity, it made it easier to hold the box (reduced flexor digitorum and anterior deltoid activity) in both AC and PC and significantly reduced perceived effort during both carriage techniques (Kudryk, 2008).

Intersegment coordination is important for functional movements such as walking or load carriage. Transverse pelvic rotation...
is used as a means to increase stride length during healthy, unloaded gait (Stokes et al., 1989; Wagenaar and Beek, 1992). In order to reduce total body angular momentum and improve efficiency of movement, the trunk counter-rotates the pelvis (Stokes et al., 1989). In load carriage with heavily loaded backpacks, an in-phase coordination between the trunk–pelvis is better than an out of phase (anti-phase) coordination (LaFiandra et al., 2002; Sharpe et al., 2008) (Fig. 2). In-phase trunk–pelvis coordination is used as a means to reduce the magnitude of torque that is transferred to the upper body (LaFiandra et al., 2002, 2003). The addition of a hip belt to the backpack helps to create a phase advance of the backpack to the trunk, and is suggested to further assist with the control of upper body rotational torque (Sharpe et al., 2008).

Since intersegment coordination is important during load carriage, it is important to assess the differences during anterior and posterior hand-held carriage, as well as with and without the MAD. It was hypothesized that the posterior load carriage technique would exhibit a more in-phase and less variable coordination pattern than that of the anterior load carriage technique. Based on backpack research it was hypothesized that the MAD would cause a more in-phase trunk–pelvis coordination, which should help to decrease the risk of injury (LaFiandra et al., 2002; Sharpe et al., 2008).

2. Methods

2.1. Participants

Thirteen healthy males with no reported bodily pain and no professional moving experience were recruited and participated in this study (Table 1).
Data collection took place on a Sports Art Fitness 6300 treadmill (Sports Art Fitness, Woodsville, WA) (Fig. 3A). Kinematic data for this study were collected using six Vicon 512 motion capture cameras (Oxford Metrics Group, UK) at a rate of 120 Hz. Four retro-reflective markers (25 mm diameter) were affixed to the end corners of the treadmill to define a treadmill coordinate system in which the body segments were tracked (Fig. 3B). Box motion was tracked using three non-collinear retro-reflective markers affixed to the box (Fig. 3B). Two rigid triads of 3 retro-reflective markers were affixed to participants’ pelvis and the thorax via nylon and elastic straps (Fig. 3C). The superior edge of the straps fixing the triads to the trunk and pelvis were aligned approximately 13 mm below the participants’ drinking and at the level of the ASIS, respectively (LaFlandra et al., 2003). The triads were moved anterior when executing the posterior carries, and moved posterior when the anterior carries were executed to ensure that neither the MAD nor the box obstructed from camera view. Each time the markers were moved, an anatomical reference trial was taken. An individual retro-reflective marker was also affixed to the posterior aspect of each subject’s heel. Participants were fitted with the Mover’s Assistive Device as described by Kudryk (2008) (Fig. 3). After each condition, participants rated their physical discomfort for a variety of areas of the body on a scale of 1 to 10, where 1 was representative of negligible discomfort and 10 was representative of extreme discomfort (Ong and Seymour, 2004). Areas included in the questionnaire were: (1) hands, (2) arms, (3) shoulders, (4) upper/middle back, and (5) lower back. Participants were informed that this discomfort was to be an overall discomfort for each area that could pertain to joint discomfort as well as muscular discomfort. At the end of the session, participants were asked to rate their order of preference of load carriage technique assuming they were moving objects for a prolonged period of time between a house and a moving truck.

2.3. Data processing

All data analyses were performed using custom Matlab software (The MathWorks, Natick, MA, USA). All kinematic data were dual-pass filtered using a 2nd order low-pass Butterworth filter with cutoff frequencies ranging between 6.2 to 8.3 Hz (Winter, 2009). Optimal cutoff frequencies for each participant were calculated through a residual analysis of the difference between filtered and unfiltered signals over a wide range of cutoff frequencies (Winter, 2009; Wells and Winter, 1980). Marker coordinate systems were defined for the trunk, pelvis and box (Deluzio and Astephen, 2007; Graham et al., 2011) and transformed into the treadmill coordinate system (Winter, 2009). Segment angular positions were calculated using a three-dimensional Euler rotation sequence (flexion-extension, abduction-adduction, internal-external rotation) and angular velocities were calculated using the first central differences method (Winter, 2009). For the purposes of this investigation only transverse plane angles and velocities were analyzed further. All segment angles and velocities were then divided into individual gait cycles defined by successive right foot heel strikes (Miller et al., 2008). Timing of the right foot heel strike was calculated using a velocity-based algorithm designed specifically for treadmill gait (Zeni et al., 2008). Angular position and velocity time series were then interpolated to 102 data points, each point representing 1% of the gait cycle (Pollard et al., 2005). The first two, and last one gait cycles were removed and not entered into further analyses to ensure steady state movement leaving a total of 52 cycles to be analyzed. Segment ranges of motion (ROM) were calculated by subtracting the minimum angle (θmin) from the maximum angle (θmax) and taking the absolute value for each gait cycle to determine if segment angles were changing as a result of the technique.

\[
\text{ROM} = \text{abs}(\theta_{\text{max}} - \theta_{\text{min}}) \quad (1)
\]

All angular positions (θ) and velocities (ω) were normalized from –1 (minimum) to 1 (maximum) at each time frame (i) to account for amplitude and frequency differences between segments using the following equations (Miller et al., 2008).

\[
\theta_{\text{norm}} = \frac{2\pi \theta_{\text{max}} - \theta_{\text{min}}}{\theta_{\text{max}} - \theta_{\text{min}}} \quad (2)
\]

\[
\omega_{\text{norm}} = \frac{\omega_{\text{max}} - \omega_{\text{min}}}{\omega_{\text{max}} - \omega_{\text{min}}} \quad (3)
\]

The normalized angular positions were plotted against the normalized angular velocities to create phase plane plots (Peters et al., 2003). Phase angles (ϕ) were calculated for each time frame of the gait cycle using the four-quadrant inverse tangent function in Matlab* (atan2) and defined as the angle from the right horizontal axis (Seay et al., 2011).

\[
\text{CRP} = \text{abs}(\phi_{\text{norm}} - \phi_{\text{Ideal}}) \quad (4)
\]

To eliminate discontinuities in the final CRP angle, any value greater than 180° was subtracted from 360°, resulting in a CRP angle in the range of 0°–180°. 0° represents an in-phase coordination and 180° represents an anti-phase coordination (Seay et al., 2011). To calculate the mean CRP, all CRP curves were ensemble-averaged at each point on the curve, and the average across all values in the stride cycle (p)
was calculated (Eq. 5). The vCRP was calculated by taking the standard deviations in CRP at each percent in the stride cycle and then averaged over the entire stride cycle (Eq. 6) (Stergiou et al. 2001) (Fig. 4).

\[
\text{Mean CRP} = \frac{\sum_{i=1}^{p} \text{CRP}_i}{p}
\]

\[
vCRP = \frac{\sum_{i=1}^{p} \text{SD}_i}{p}
\]

### 2.4. Statistical analysis

Statistical analyses in this study were performed using SPSS 20.0 (IBM Corporation, Armonk, NY, USA). Trunk and pelvis ROMs from the unloaded gait trials were entered into paired \( t \)-tests to determine if there were differences between marker positions. All experimental mean ROMs, mean CRPs, and mean vCRPs were entered into separate two-way repeated-measures ANOVAs with 2 factors: device (MAD/no MAD) and technique (AC/PC). Conversely, ordinal rating of perceived exertion data were analyzed across the four conditions using Friedman’s non-parametric repeated-measures ANOVA by ranks. Calculated \( F \) and \( \chi^2 \) values greater than the critical values at \( \alpha = 0.05 \) were considered statistically significant.

### 3. Results

No significant differences in pelvis or trunk ROM (\( p = 0.481 \) and \( p = 0.268 \), respectively) were found across the anterior and posterior technique marker positions ensuring differences across techniques were movement related. No significant main effects of device, technique or any interactions were found for mean box-
However, for the mean transverse plane trunk–pelvis CRP, there was a significant difference for device (MAD /no MAD). A significant interaction between the device and technique indicated the mean CRP decreased significantly more with the use of the MAD in the PC than it did with the AC (Table 2). No significant effects ($p > 0.05$) of device or technique were found on the vCRP between the trunk-pelvis. While there was also no significant main effect of device on the vCRP between the box-trunk, there was a significant effect of technique. The anterior carriage technique exhibited lower variability, which is considered to be a more steady coordination pattern when compared to the posterior carriage condition (Table 2).

Wearing the MAD significantly decreased the transverse ROM of the pelvis and the box, but had no effect on the trunk ROM (Table 2). However, for the mean transverse plane trunk–pelvis CRP, there was a significant difference for device (MAD /no MAD). A significant interaction between the device and technique indicated the mean CRP decreased significantly more with the use of the MAD in the PC than it did with the AC (Table 2). No significant effects ($p < 0.05$) of device or technique were found on the vCRP between the trunk-pelvis. While there was also no significant main effect of device on the vCRP between the box-trunk, there was a significant effect of technique. The anterior carriage technique exhibited lower variability, which is considered to be a more steady coordination pattern when compared to the posterior carriage condition (Table 2).

For the upper limb, the anterior carriage technique was ranked better (less perceived discomfort) than the posterior carriage technique. Conversely, for the lower back the posterior technique was ranked better than the anterior technique. In both cases, the assisted condition was ranked superior than the non-assisted condition. When asked which of the four conditions participants preferred, the majority ranked the anterior carriage condition (AAC) best, followed by the assisted posterior carriage (APC), unassisted anterior carriage (UAC), and finally the unassisted posterior carriage (UPC). Therefore within each AC/PC condition, users preferred using the MAD.

### 4. Discussion

The primary objective of this investigation was to quantify differences in intersegment coordination between the trunk–pelvis and the box–trunk during two different hand-held load carriage techniques. A secondary aim of the investigation was to quantify differences in intersegment coordination with and without the use of an on-body assistive device, designed specifically for professional movers.
It was hypothesized the posterior load carriage technique would exhibit a more in-phase and a more steady coordination pattern than that of the anterior load carriage technique. Expert manual handlers tend to adopt safer handling techniques and postures than novices (Authier et al., 1996). Unlike unloaded gait where it has been suggested that the goal of movement is to counter-balance torques between the upper and lower body (Stokes et al., 1989), the goal of load carriage is to decrease the rotational torque experienced on the upper body defined as the thorax and arms (LaFiandra et al., 2002, 2003; Sharpe et al., 2008). Through an in-phase trunk-pelvis coordination, less muscular activity may be required to control the angular momentum of the load and the risk of injury due to high rotational loads could potentially be reduced (LaFiandra et al., 2002).

Contrary to the hypothesis, the present experiment did not find any significant technique differences for the mean trunk–pelvis CRP; however, both techniques exhibited a mean trunk-pelvis CRP that was closer to being in-phase coordination (CRP of 0°) than anti-phase coordination (CRP of 180°). Interpretations of transverse plane trunk coordination and kinetic differences during load carriage have lead researchers to suggest the goal of load carriage movement is not only to minimize the magnitude of upper body torque, but also to maintain a steady coordination pattern (LaFiandra et al., 2002, 2003; Sharpe et al., 2008). While no differences in CRP variability were seen across technique between the trunk–pelvis, the anterior carriage displayed a significantly decreased vCRP between the box–trunk in comparison to the PC technique. This decreased variability in the anterior carriage may have been a result of better hand coupling to the box.

The increased ratings of perceived discomfort in the upper limbs during the posterior carriage are likely attributable to the standardized arm position participants were required to assume. The right arm was extended directly posterior and near the end range of motion for most participants, and may be a likely cause for the increased perceived discomfort. Despite the unfamiliarity of the technique, the posterior technique exhibited lower perceived rating of discomfort in the lower back, the site of pain that was reported to be the most severe amongst professional movers (Kudryk, 2008). The posterior technique seems to be beneficial in improving low back comfort; and the anterior technique is more beneficial in improving upper limb comfort. It is important to consider that while the posterior carriage may be more beneficial for back health, the upper extremities may be at an increased risk for upper extremity injuries, which may develop from awkward postures during the carriage (Williams and Westmorland, 1994).

The more synchronous coordination between the trunk and pelvis with the use of the MAD can be interpreted as a mechanism to decrease the transmission of torque to the upper body, thereby decreasing the muscular effort required to control the angular momentum of the load (LaFiandra et al., 2002, 2003). The use of a hip belt when carrying a heavily loaded backpack resulted in a more anti-phase coordination between the box and trunk when compared to a backpack with no hip belt (Sharpe et al., 2008). The backpack slowed and reversed directions before the trunk, via the direct connection to the pelvis and was considered to be helpful in the control of rotational torque experienced at the trunk (Sharpe et al., 2008). The present study found no differences in the box–trunk mean CRP between assisted and unassisted conditions. It is likely the connection between the loaded box and the MAD was not secured strongly enough by the hands; therefore the hip belt did not affect the coordination between the box and trunk. This reduction in upper body torque during hand-held load carriage with the MAD occurs exclusively through in-phase trunk–pelvis coordination.

The MAD reduced discomfort in all body areas examined, except for the upper back, where no significant differences were found between the assisted and unassisted conditions. Since the back, shoulders and hands were identified as the most common and severe locations of pain among movers (Kudryk, 2008), a device that lowers perceived discomfort in these areas, as well as in the arms, may help to contribute to a reduction of injuries when movers use the MAD as an assistive device while on the job.

Although researchers ensured all participants received time to become familiar with both carriage techniques and the MAD, a lack of availability of professional mover volunteers may have affected the findings. Since experienced movers prefer to use the PC technique while on the job (Kudryk, 2008), it is believed that a more in-phase trunk–pelvis coordination and a decreased variability of the coordination might be present among professional movers. Coordination is a speed dependent variable, and in order to test for true differences across conditions it was necessary for all data collection to occur on a treadmill to control for speed (Dingwell and Marin, 2006). However, there is a difference in coordination between treadmill and overground walking (Dingwell et al., 2001); therefore, the findings from this coordination study may not be entirely transferrable to professional movers in the field.

The present study was designed to compare the transverse plane intersegment coordination between the trunk–pelvis and the box–trunk during two different hand-held load carriage techniques as well as with and without the assistance of the MAD. While no differences in coordination were seen between the AC and PC conditions, both techniques exhibited an in-phase trunk–pelvis coordination, which is believed to be a mechanism to reduce the risk of low back injury (LaFiandra et al., 2002). More research is still required in the examination of safe carriage practices across different hand-held load carriage techniques. The MAD demonstrated a more in-phase trunk–pelvis coordination, and thus minimized the angular displacement between the two segments which has been suggested to help decrease the magnitude of upper body torque (LaFiandra et al., 2002, 2003). The decreases in participants’ ratings of perceived discomfort in the upper extremities and low back further support the use of the MAD during hand-held load carriage. Moreover, when asked to rate their preferred technique, the majority of participants reported they would use the assisted techniques before the unassisted techniques.
Conflict of interest statement

There are no known conflicts of interest.

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References


