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Comparison of trunk stiffness provided by different design characteristics of lumbosacral orthoses

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Abstract

Background—Lumbosacral orthoses (LSOs) are class I medical devices that are used in conservative and postoperative management of low back pain. The effectiveness of LSOs depends on their design aimed at enhancing trunk stiffness. Therefore, the purpose of this study was to compare two lumbar supports: extensible (made of neoprene and lycra) and nonextensible (made of polyester and nylon).

Methods—Trunk stiffness and damping was estimated from trunk displacement data in response to a quick force release in trunk flexion, extension, and lateral bending. 14 male and 6 female subjects performed 5 trials at each experimental condition: 1) No LSO, 2) extensible LSO, 3) non-extensible LSO, 4) non-extensible LSO with a small rigid front panel, and 5) non-extensible LSO with a large rigid front panel. Testing order was randomized and the LSOs were cinched to a pressure of 70 mmHg (9.4 kPa) measured between posterior aspect of the iliac crest and the orthosis.

Findings—The non-extensible LSO reduced trunk displacement by 14% and increased trunk stiffness by 14% ($p < 0.001$). The extensible LSO did not result in any significant change in trunk displacement or stiffness. The addition of rigid front panels to the non-extensible LSO did not improve its effectiveness. The trunk damping did not differ between the LSO conditions.

Interpretation—A non-extensible LSO is more effective in augmenting trunk stiffness and limiting trunk motion following a perturbation than an extensible LSO. The rigid front panels do not provide any additional trunk stiffness most likely due to incongruence created between the body and a brace.

Keywords

Lumbar Spine; Stability; Low Back Pain; Abdominal Belts

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1. Introduction

Lumbosacral orthoses (LSOs) are class I medical devices that are used in conservative and postoperative management of low back pain (LBP). In non-medical applications, such as prophylaxis or ergonomic aid, they are referred to as abdominal supports, lumbar supports, and abdominal belts. Therefore, the terms “belts”, “supports” and “orthoses” will be used synonymously in this paper.

A systematic review of large prospective studies within the framework of the Cochrane Back Review Group concluded that there is some evidence suggesting that lumbar supports are an effective treatment for LBP but it is still uncertain whether lumbar supports are more effective than other interventions (Jellema et al., 2001). The mechanisms by which the LSOs might be effective in alleviating symptoms of LBP are also unclear.

Several hypotheses have been proposed about the mechanisms of LSOs, but the only well-supported ones pertain to the restriction of motion and augmentation of trunk stiffness. While it appears that LSOs do reduce gross trunk range of motion to some extent (Axelsson et al., 1992; Krag et al., 2003), this effect may be limited only to the upper lumbar levels (Axelsson et al., 1992; Norton and Brown, 1957; Tuong et al., 1998). Intervertebral translations are not reduced at all (Axelsson et al., 1992). On the other hand, increased trunk stiffness due to LSOs has been shown consistently (Cholewicki et al., 1999; Ivancic et al., 2002; Lavender et al., 2000; McGill et al., 1994). Cholewicki (2004) and Cholewicki et al. (2007) developed a theory that this increase in stiffness may bring about an equivalent decrease in trunk muscle co-contraction in patients with LBP (Cholewicki, 2004; Cholewicki et al., 2007). In turn, the reduction in low level, tonic muscle activity sustained during postural tasks, could alleviate some of the symptoms associated with muscle fatigue and pain. Based on this theory, the extent to which a brace can be effective will depend on its design aimed at enhancing trunk stiffness.

Several different brace designs exist. They can be roughly grouped into three categories based on the material: extensible made of neoprene or rubber, non-extensible made of canvas or nylon, or rigid made of molded hard plastic. Other features may include raised front or back panels that increase contact area with the body. While several comparisons of motion restriction between various LSOs exist in the literature (Axelsson et al., 1992; Cholewicki et al., 2003; Krag et al., 2003), there are no data comparing their effectiveness in enhancing trunk stiffness. Therefore, the purpose of this study was to compare two lumbar supports: extensible and non-extensible. In addition, the effect of a rigid front panel added to the non-extensible brace was examined. Two hypotheses were tested: 1) a non-extensible LSO will increase trunk stiffness more than an extensible LSO, and 2) the addition of the abdominal panel will further enhance the effectiveness of the non-extensible LSO.

2. Methods

14 male (median age 22, range 20–50; median height 183, range 168–196 cm; median weight 81.8, range 77.3–100.0 kg) and 6 female (median age 23.5, range 18–46; median height 170, range 168–178 cm; median weight 64.3, range 50.0–80.5 kg) subjects volunteered for this study. Because each subject was his or her own control, nobody was excluded based on their history of LBP. However, all subjects were in general good physical health and none of them had previous spinal surgery. The research protocol was approved by the Institutional Review Board and complied with the Declaration of Helsinki.

Stiffness and damping were estimated from the trunk kinematic response to sudden load release (quick release). Each subject performed isometric exertions in trunk flexion, extension, and lateral bending in a specially designed apparatus that restrained hip motion, leaving the upper body free to move in any direction (Figure 1). A cable attached to a chest harness at

approximately the T5 spinal level served as a resisting force held with an electromagnet. The subject pulled against the cable until he/she reached a target force displayed on an oscilloscope (100 N for men or 70 N for women). An experimenter released the electromagnet at a random time interval within 0 to 5 seconds after the target force was reached, and the subject was required to stop the ensuing trunk motion/perturbation.

LSOs made of extensible (neoprene and lycra) and non-extensible (polyester and nylon) materials were compared. The Adjustable Back Brace (Mueller Sports Medicine, Inc., Prairie du Sac, WI, USA) served as an example of an extensible brace and the QuikDraw Pro (Aspen Medical Products Inc., Long Beach, CA, USA) was used as an example of a non-extensible brace. In addition, the Aspen LSO came with two optional, rigid front panels: small and large (Figure 2). Five trials, separated with approximately 30-second rest breaks, were performed in each direction for each of the 5 experimental conditions: 1) Control (No LSO), 2) extensible LSO (Mueller), 3) inon-extensible LSO (Aspen), 4) non-extensible LSO with a small front panel (Aspen SP), and 5) non-extensible LSO with a large front panel (Aspen LP). Testing order was randomized. To standardize tension in the orthoses, LSOs were cinched to a pressure of 70 mmHg (9.4 kPa) measured with the Therapoint device (Roho, Inc., Belleville, IL, USA) inserted between posterior aspect of the iliac crest and the orthosis.

Force in the cable (custom strain gauge) and trunk acceleration (CXL04LP3 accelerometer, Crossbow Technology, Inc., San Jose, CA, USA) data were recorded at 1600 Hz for 1 second prior to and 2 seconds after the release. Trunk acceleration was digitally integrated twice to obtain linear displacement. Knowing the distance between the trunk's center of rotation (Stokes, 1987) and the accelerometer placement (approximately T5), linear trunk displacement was converted to angular displacement. Subsequently, the effective trunk stiffness was estimated using the methodology previously described (Cholewicki et al., 1999). The trunk was represented by a second order, inverted pendulum model. Its angular displacement response (θ) following the force release is determined by the trunk, inertia (I), damping (B) and stiffness (K) (Eqns 1 and 2):

$$I\ddot{\theta} + B\dot{\theta} + K\theta = mgL\sin\theta \quad (1)$$

$$I\theta + B\int\theta dt + K\iint\theta dt^2 + Ct^2 = mgL\iint\sin\theta dt^2 \quad (2)$$

where C is the constant related to the release force, mg is trunk weight, and L is the height measured from the L4 spinous process to the center of trunk mass, assumed to be at the T9 level. Muscle reflex response affects the angular trunk displacement after the release (Cholewicki et al., 2000). Therefore, the stiffness (K) and damping (B), are called the "effective trunk stiffness" and "effective trunk damping", because they combine the effects of the trunk muscles' stiffness and damping established prior to the release and the muscle reflex response following the release (Cholewicki et al., 2000). The parameters B , K , and C were obtained by fitting the Eqn. 2 to the experimental data $\theta(t)$, according to previously established method (Cholewicki et al., 1999; Cholewicki et al., 2000), while I was computed as 53.6% of body weight times L^2 (Winter, 2005).

Both angular displacement and stiffness data were analyzed with a two factor (LSO condition and the direction of release), repeated measures ANOVA to test our hypotheses. Tukey's post-hoc test was used for pairwise comparisons among LSO conditions. In the cases where data were not normally distributed (according to Anderson-Darling test), the Box-Cox transformation was performed prior to statistical analyses. If this transformation failed to

correct data distribution, a non-parametric Kruskal-Wallis test was used. The significance level was set at $p=0.05$. All statistical analyses were performed with Minitab 13.1 software (Minitab Inc., State College, PA).

Given the importance of damping in the stability of dynamic systems, damping data were also analyzed with a two factor repeated measures ANOVA for the main effects of LSO conditions and directions.

3. Results

The type of LSO significantly affected trunk displacement ($DF=4$, $F=6.4$, $p<0.001$) and effective trunk stiffness ($DF=4$, $F=5.6$, $p<0.001$). Similarly, the direction of release also had significant effects on trunk displacement ($DF=2$, $F=11.9$, $p<0.001$) and stiffness ($DF=2$, $F=12.1$, $p<0.001$). However, no significant interactions existed between LSO type and release direction (Tables 1 and 2).

3.1. Angular Displacements

The Aspen LSO resulted in significantly smaller displacements, following trunk perturbations, than the Mueller LSO ($T=4.1$, $p<0.001$) or No LSO ($T=3.3$, $p=0.009$) (Figure 3). On average, the Aspen LSO reduced 14% of trunk displacement that resulted from the sudden force release when compared to the No LSO condition. In contrast, the Mueller LSO had no significant effect on trunk displacement. Contrary to our hypothesis, the addition of front panels to the Aspen LSO did not improve its effectiveness in reducing trunk motion (Figure 3).

3.2. Trunk Stiffness

The effective trunk stiffness followed a pattern similar to trunk displacement data. The Aspen LSO increased significantly trunk stiffness in comparison to the Mueller LSO ($T=3.6$, $p=.003$) or the No LSO condition ($T=2.7$, $p=.048$) (Figure 4). On average, the Aspen LSO resulted in a 14% increase in the effective trunk stiffness, while the Mueller LSO had no significant effect. The addition of front panels to the Aspen LSO did not improve its effectiveness (Figure 4).

3.3. Trunk Damping

The effective trunk damping did not differ between the LSO conditions ($DF=4$, $H=2.2$, $p=0.700$). There was, however, a main effect of quick release direction ($DF=2$, $H=107.4$, $p<0.001$). On average, damping coefficients were 1.2(2.1) Ns/rad in extension, 4.8(8.2) Ns/rad in flexion, and 36.8(35.8) Ns/rad in lateral directions.

4. Discussion

Although many hypotheses on the mechanisms of action of LSOs were proposed in the past (Genaïdy et al., 1995), most of them must be rejected based on rigorous scientific testing. The augmentation of trunk stiffness, possibly leading to changes in trunk muscle activation, is one hypothesis that is well-supported with experimental data (Cholewicki, 2004; Cholewicki et al., 2007). This metric could be used for the comparison of various orthoses and for maximizing their effectiveness during the design process. Therefore, based on the trunk stiffness data obtained from the current study, the following design recommendations are made.

Non-extensible LSOs (Aspen) increased trunk stiffness and limited trunk motion after a perturbation, while the extensible LSOs did not have any such significant effects. To gain more insight into the material properties of these two orthoses, we tested them by applying load in the longitudinal direction and measuring their elongation. The Aspen LSO was much stiffer than the Mueller LSO (Figure 5). It follows then that a non-extensible orthosis, such as the

Aspen LSO, will provide greater resistance as trunk displacement increases due to a perturbation than an extensible orthosis, such as the Mueller LSO. It should be pointed out that both orthoses were cinched to the same initial tension. Thus this variable could not account for the differences found between these two orthoses. A likely explanation is that as the trunk begun to displace, tension in the non-extensible orthosis increased more rapidly than tension in the extensible orthosis.

Averaged across the three directions, the Aspen QuikDraw Pro LSO augmented effective trunk stiffness by 14%. By comparison, we measured 31% increase in trunk stiffness in a previous study using the same protocol, but a wider Aspen LSO made of a thin, flexible plastic (Cholewicki et al., in review). In addition, that LSO was stiffer than the QuikDraw Pro. Therefore, there is probably an advantage to a material that does not easily buckle as the trunk displacement angle increases.

Rigidity of the material does not necessarily guarantee the effectiveness of a brace. For example, in the current study, the addition of rigid panels did not improve the brace performance. In another study, we compared the Aspen flexible thoraco-lumbo-sacral orthosis (TLSO) with a rigid, turtle shell-type, TLSO. Both braces provided similar trunk motion restriction and resulted in similar effective trunk stiffness (Cholewicki et al., 2003). Krag et al. (2003) also reached the same conclusion that a rigid LSO did not differ from a flexible LSO design in terms of the trunk motion restriction (Krag et al., 2003). Therefore, there is likely a trade-off between material rigidity and shape congruence with a person's trunk. Muscles and other soft tissues change the contour of the body as various trunk motions take place. This complex interaction between the soft tissue and a brace must be taken into consideration when optimizing the brace design. While the softer material conforms better to the body's contour, the stiffer brace might be better suited for restricting trunk motion. At the same time, the stiffer brace might allow too much motion between the brace and the surface of the body. Finally, soft plastic or nylon LSO designs might increase patients' compliance, because they offer more comfort than rigid braces (Krag et al., 2003).

The current study was limited to the comparison of only two LSOs. There are a large number of various braces on the market. It is likely that other design features also play a role in determining the effectiveness of a brace. However, this study focused specifically on the comparison between extensible and non-extensible LSOs. As a result, the non-extensible Aspen QuikDraw Pro brace provided superior performance in terms of limiting trunk motion and increasing trunk stiffness in comparison to the extensible Mueller Adjustable Back Brace.

Although trunk damping did not significantly change between conditions, it is possible that true differences might exist between LSOs, which might also be important to consider. Given the large standard deviation in the prediction of trunk damping, it is possible that any differences between conditions were obscured by noise. Because the belts significantly change abdominal geometry (Miyamoto et al., 2008; Miyamoto et al., 2002), it seems plausible that a LSO can alter displacement of the abdominal content, thus changing damping properties of the spine. However, more precise methods are required to assess damping in the in vivo spine than are presented in the current paper.

5. Conclusions

- The non-extensible Aspen LSO was more effective in augmenting trunk stiffness and limiting trunk motion following a perturbation than the extensible Mueller LSO.
- The rigid front panels attached to the non-extensible LSO did not provide any additional trunk stiffness.

- The effective trunk damping did not differ between the LSO conditions.

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Figure 1. A subject positioned in a multidirectional, quick force release apparatus. (A) Flexion, (B) extension and (C) lateral bending load application and release.

Figure 2.

(A) An extensible (Adjustable Back Brace, Mueller Sports Medicine, Inc., Prairie du Sac, WI, USA) and (B) a non-extensible (Quick Draw Pro, Aspen Medical Products Inc., Long Beach, CA, USA) LSOs were compared. Also shown, are the (C) small and (D) large front panels that attach to the non-extensible LSO.

Figure 3.
The effects of various LSO designs on the trunk displacement following quick force release.
The brackets indicate significant differences in post-hoc pairwise comparisons ($p \leq 0.05$).

Figure 4.

The effects of various LSO designs on the effective trunk stiffness estimated from kinematic data following quick force release. The brackets indicate significant differences in post-hoc pairwise comparisons ($p \leq 0.05$).

Figure 5.

Material properties (force-elongation) of the Aspen and Mueller LSOs. By a comparison, they can be referred to as a non-extensible and an extensible orthosis, respectively. A horizontal line at 150N indicates the approximate tension required to achieve a pressure of 70 mmHg (9.4 kPa) between posterior aspect of the iliac crest and the orthosis.

Table 1

The effects of various LSO designs on trunk displacement (deg) response to quick force release in extension, flexion, and lateral bending directions. Significant main effects of the LSO design and release direction were present ($p \leq 0.05$).

	No LSO	Mueller	Aspen	Aspen SP	Aspen LP
Extension	7.5 (3.1)	7.9 (3.0)	6.6 (3.5)	7.4 (4.1)	6.3 (2.8)
Flexion	8.9 (4.9)	9.1 (4.4)	7.8 (4.2)	8.0 (4.9)	7.6 (3.2)
Lateral	9.2 (3.6)	9.0 (2.8)	7.7 (3.3)	7.7 (2.7)	7.5 (2.5)

The effects of various LSO designs on the effective trunk stiffness (Nm/rad) estimated from kinematic data following quick force release in extension, flexion, and lateral bending directions. Significant main effects of the LSO design and release direction were present ($p \leq 0.05$).

Table 2

	No LSO	Mueller	Aspen	Aspen SP	Aspen LP
Extension	359 (146)	333 (134)	379 (140)	372 (156)	397 (157)
Flexion	382 (152)	360 (148)	410 (206)	401 (150)	408 (155)
Lateral	395 (241)	405 (218)	509 (262)	492 (305)	479 (238)