Trunk kinematics under sudden loading impact when adopting different foot postures

The purpose of this study was to explore the effect of foot posture on trunk biomechanical responses when experiencing sudden external loading. Fifteen subjects were recruited to perform a series of sudden loading tasks using three different foot postures with two levels of weight. Our results showed that sudden external loading generated smallest spinal impact when subjects adopted "separate" foot posture. Heavier load resulted in larger impact but there was no interaction effect between foot posture and magnitude of the load. This knowledge could be used in reducing the risk of low back pain when dealing with sudden loading.

INTRODUCTION

Low back pain (LBP) is a worldwide problem (Walker, 2000) which leads to substantial economic cost (Lambeek, 2011). Previous studies have identified sudden loading during manual material handling as a major contributor to low back injury (Manning, 1984; Lavender, 1989; McCoy, 1997). When an external loading suddenly applies to the musculoskeletal system, it initiates trunk muscle force exertion to minimize postural perturbation (Lavender, 1989). This natural muscle reaction increases trunk stiffness and stability (Granata, 2000). However, it also increases lumbosacral joint loading which may lead to low back injury (Lavender, 1993).

Previous studies investigated several strategies to cope with sudden loading, such as anticipatory postural adjustments (APA) (Aruin, 1995; Lavender & Marras, 1995; Lavender, 1993) and training or experience (Lawrence, 2004; Lavender, 1993). However how would different foot postures change trunk biomechanical responses during sudden loading has not been explored. Previous studies showed that different foot stance might generate significantly different spinal loading during manual material lifting (Cholewicki, 1991; Sorensen, 2011). Another study discovered that foot postures significantly influenced the standing balance (Kirby, 1987). According to these previous findings, the purpose of the current study was to investigate the effect of foot posture on trunk kinematics and the corresponding spinal loading when experiencing sudden external loading. The interaction effect of foot posture and weight of the load was also investigated.

METHOD

Subjects

Fifteen male subjects with no previous history of low back pain or upper extremity injuries were recruited from the student population. All subjects signed informed consent document before their participation.

Experimental Design

Two independent variables were involved in this study: foot posture and weight of the load. As shown in Figure 1, three different foot postures were tested in the experiment: 1. Close Feet (CF): 5 cm lateral clearance between the medial sides of both ankles; 2. Open Feet (OF): 30 cm lateral clearance between the medial sides of both ankles and 3. Separate Feet (SF): 30 cm lateral and 40 cm anterior-posterior clearances between the medial sides of both ankles. It was assumed that, in upright standing posture the center of lumbosacral joint (referred as L5/S1 joint later) is projected at the midpoint between ankles (Waters, 1993). In the current study it was designed such that the midpoint between ankles in all three foot postures lies on the same location. In addition, the distances between the midpoint of ankles and the projected center of mass of external load were kept constant among all conditions. In such, the initial impact of sudden loading on lumbosacral joint was controlled. Two different weights (6.8 kg and 3.4 kg) were included to test the interaction effect between foot posture and the magnitude of the load. The combination of the two independent variables created 6 conditions. Each condition was tested for 3 times, therefore resulted in a total of 18 trials.

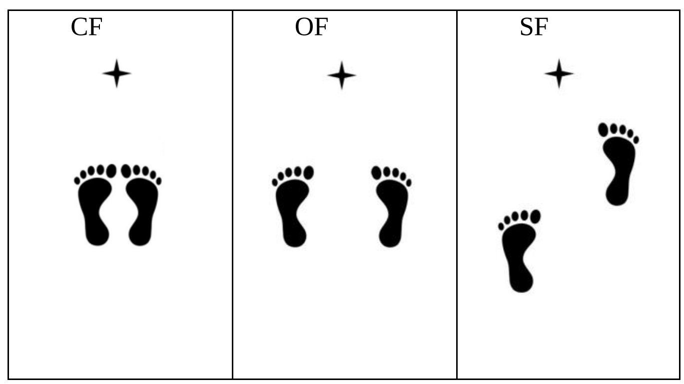

Figure 1. Three different foot postures.

The dependent variables were: 1. spinal moment, which was defined as the moment difference between the initial L5/S1 moment and the peak L5/S1 moment during sudden loading; 2. trunk flexion angle, which was defined as the difference between the initial trunk angle (at upright posture) and the peak trunk flexion angle during sudden loading; 3. peak L5/S1 joint compression force and 4. peak L5/S1 joint shear force during sudden loading.

Apparatus and Equipment

A wood frame was built, so that a rope that controlled by an experimenter could hang the loads at the shoulder level of subjects (Figure 4). The loads were made of disc weights with a PVC pipe mounted in the center hole and worked as handles (Figure 2).

An eight-camera (MX-13 series) 3D optical motion capture system (Vicon, Nexus, Oxford, UK) was used to capture subjects' trunk and upper extremities kinematics. A surface electromyography (EMG) system (Model: Bagnoli, Delsys Inc, Boston, MA, USA) was used to collect the muscle activity data from four pairs of trunk muscles: L3 paraspinal, L4 paraspinal, rectus abdominus and external obliques. Maximal EMG data from all muscles were collected while performing maximum voluntary contraction (MVC). A Lumbar dynamometer with back flexion-extension module (Humac Norm, CSMi, MA, USA) was used to secure pelvis and provide static resistance. The placements of Vicon markers and EMG electrodes are demonstrated in Figure 3.

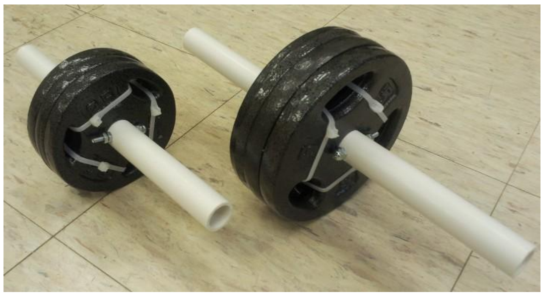

Figure 2. The loads used in the experiment.

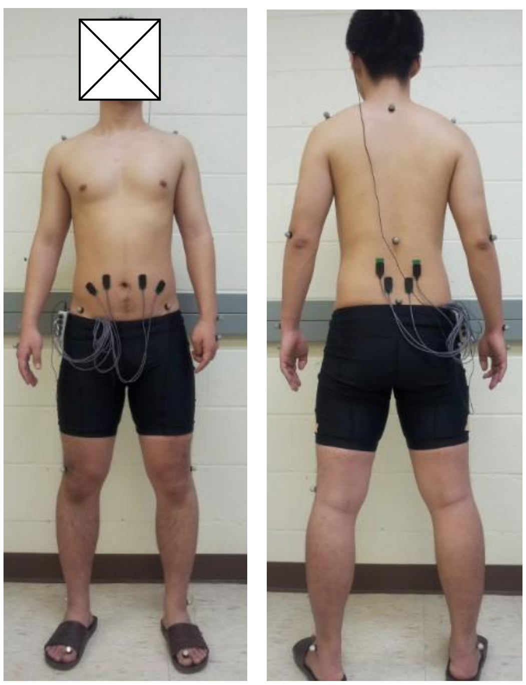

Figure 3. The placements of Vicon markers and EMG electrodes

Procedure

Upon arrival, experiment procedures were explained and the informed consent forms were signed. Subjects first performed a five minutes warm up section in order to warm up muscles. When finished, eight bi-polar surface EMG electrodes were fitted bilaterally to the above mentioned trunk muscles. Subjects were then secured to the back flexion-extension module and conducted maximum voluntary contraction (MVC) trials while EMG signals were recorded. Next, nineteen reflective markers were attached, and subjects performed designated 18 trials as is shown in Figure 4. For each trial, subjects were required to hold the handle of the load firmly (without supporting the weight of the load) with their eyes closed; the experimenter will then release the load without notice. Subjects were asked to respond to the sudden loading as quickly as possible and bring the load back to its original height (shoulder height) and hold steady for three seconds. All 18 trials were completely randomized, and ample rest was provided between trials.

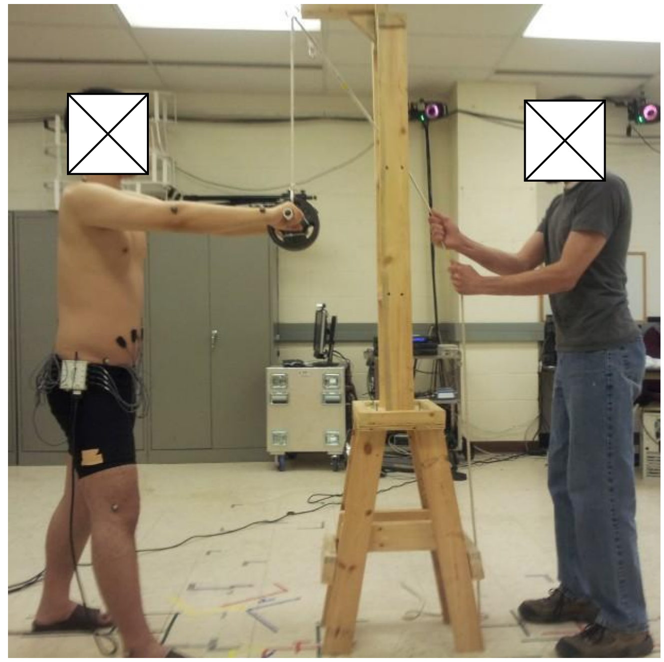

Figure 4. Subject performed the designated trial.

Biomechanical Model

A previously established EMG-assisted biomechanical model was adopted (Marras & Granata 1997; Ning, 2012) in the current study to estimate the external and internal moment about L5/S1 joint, spinal compression and shear forces were also estimated based on model output. In the current model, parameters such as moment arms and cross sectional areas of the muscles were obtained from previous studies (Jorgensen, 2001; Marras, 2001). The muscle gain was calculated by matching the external and internal moments during static load holding period (i.e. the last three seconds) of each trial, and applied to all muscles and trials for each subject.

Data Processing

Nexus 10.7 software was used to simultaneously capture both reflective markers data and record muscular EMG. Trunk and upper extremities kinematics data exported from the software was then used as inputs to calculate trunk flexion angle and L5/S1 external moment.

EMG data was notch filtered at 60 Hz and their aliases, then rectified and smoothed with a 200 data point (0.2 second) sliding window. EMG signals of experimental trials were normalized with respect to MVC EMG value of each muscle. The normalized EMG values worked as inputs of the biomechanical model to calculate internal moment, compression and shear forces of L5/S1 joint.

Statistical Analysis

Multivariate analyses of variance (MANOVA) were first conducted. Independent variables and their interactions that were found to be significant in the MANOVA were further analyzed in univariate ANOVA. Then Tukey-Kramer *post-hoc* tests were performed to further investigate the significant effects between different levels. Criteria *p*-value of 0.05 was used for all statistical tests.

RESULTS

Result of MANOVA revealed significant effects of both independent variables: foot posture and weight of loads; however the effect of their interaction was not significant therefore was not further tested. Univariate ANOVA demonstrated that both foot posture and weight significantly affected trunk flexion angle, L5/S1 moment and peak L5/S1 joint shear force. However the peak L5/S1 joint compression force was only affected by weight, but not foot posture (Table 1).

		ANOVA			
IVs	MANOVA	Trunk angle	L5/S1 moment	L5/S1 compression	L5/S1 shear
FP	P<0.001	P<0.001	P<0.001	P=0.41	P<0.001
W	P<0.001	P<0.001	P=0.007	P<0.001	P<0.001
FP*W	P=0.1	N/A	N/A	N/A	N/A

Table 1: The results of MANOVA and univariate ANOVA. IVs: Independent variables; FP: Foot posture; W: Weight.

The *post-hoc* analysis revealed that the largest trunk flexion angle, L5/S1 joint moment and shear force were generated under OF condition, whereas the smallest impact was observed under SF condition (Figure 5 to Figure 7).

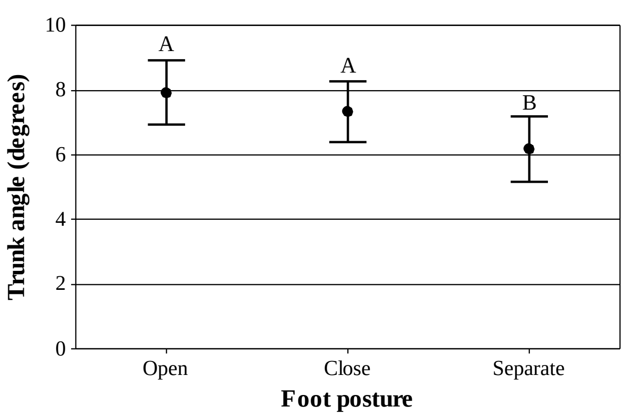

Figure 5: Peak increase in trunk flexion angle caused by sudden external loading under the three different foot posture conditions. Different letters demote angles that are statistically different from one another. Bars indicate the corresponding 95% confidence interval.

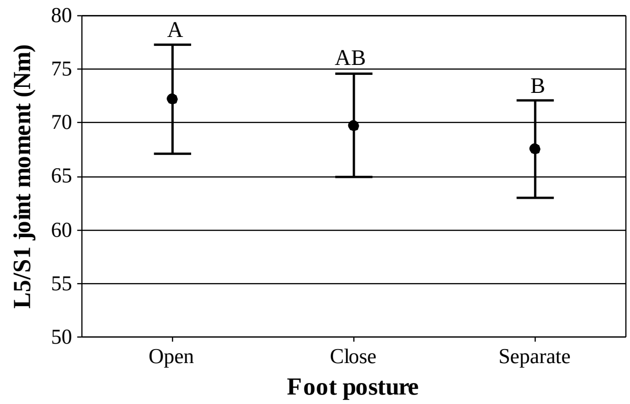

Figure 6: Peak increase in L5/S1 joint moment caused by sudden external loading under the three different foot posture conditions. Different letters demote moments that are statistically different from one another. Bars indicate the corresponding 95% confidence interval.

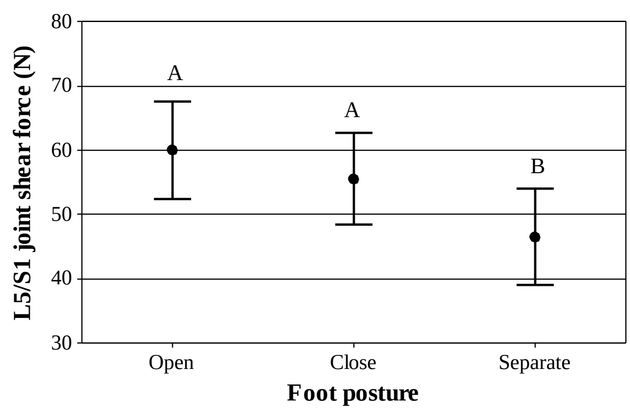

Figure 7: Peak L5/S1 joint shear force caused by sudden external loading under the three different foot posture conditions. Different letters demote forces that are statistically different from one another. Bars indicate the corresponding 95% confidence interval.

When compared the results between 6.8 kg and 3.4 kg conditions, as expected smaller impact was constantly observed under the 3.4 kg condition (Table 2).

Weight (kg)	Trunk angle (degrees)	L5/S1 moment (Nm)	L5/S1 compression (N)	L5/S1 shear (N)
3.4	5.4	53.4	1790.0	38.8
6.8	8.9	86.6	2536.1	69.7

Table 2: Results of dependent variables at different external loading levels.

DISCUSSION

Based on our results, given that SF posted the smallest trunk flexion angle, L5/S1 joint moment and peak L5/S1 joint shear force, it was generally considered as the most preferred posture followed by CF and OF which posted the larger trunk flexion and spinal loading. To better interpret these results the effect of foot posture on stability must be understood. An early study found that by increasing feet separation distance in anterior-posterior or mediolateral direction, the sway of center of pressure (COP) also increased along that direction (Kirby, 1987). Later, Holbein suggested that such increase in the range of COP displacement enlarged one's functional stability region which indicated an improved standing stability (Holbein, 1997, Holbein, 2007). According to these findings, compared with the other two foot postures, SF condition has the largest feet displacement and therefore indicates the highest level of standing stability among the three foot postures. From anatomy and geometry point of view, subjects placed one foot forward and one backward in SF posture to form a stable triangle structure along the direction that the load fell. The frontal foot could become a pivot on which ground reaction force provided counteracting moment to offset the external moment caused by the external loading. This mechanism could explain the reason why SF was the most desired foot posture.

However, it was not our expectation that CF generated less biomechanical stress than the OF posture, as OF is often thought to be a more stable foot posture. In the current study the triangle structure formed in OF was along medio-lateral direction, which had little effect resisting the external loading in the anterior-posterior direction. Additionally, previous research explored the influence of stance width on body motion and discovered increased legs-pelvis stiffness with the increase of stance width (Day, 1993). In the current study, compared with OF, in the CF condition, perturbation introduced by sudden loading may generate more hip motion than trunk flexion, due to its relatively lower stiffness level. As a result, sudden external loading generated more significant trunk biomechanical responses in the OF condition than the CF condition.

Regarding weight of loads, significant higher values of all four dependent variables were observed in the 6.8 kg weight condition. In addition, no significant interaction between the two independent variables was observed, which indicated that for both weight levels, the effects of the three foot postures were similar.

There are some limitations in the current study. First, we required subjects to close their eyes and keep muscles "relaxed" before the load was released in order to control the expectation of the sudden loading. However, subjects might still try to anticipate the drop of loads, which unintentionally initiated trunk muscle exertion. Second, only two relatively light weight levels were investigated in this experiment, so that lumbar muscle fatigue and the risk of injury could be controlled. However in real occupational settings, much heavier load may be experienced.

CONCLUSION

Findings of the current study will help us better understand the effects of foot posture on spinal biomechanical responses when experiencing sudden loading. Based on our results, selection of appropriate foot posture can work as a protective strategy to prevent low back injury, especially for those who have to cope with sudden loading in their work environment, such as nurses who handle patients and warehouse workers who load and unload packages.

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