THE EFFECTS OF A LOWER BODY EXOSKELETON LOAD CARRIAGE ASSISTIVE DEVICE ON LIMITS OF STABILITY AND POSTURAL SWAY

Jeffrey M. Schiffman*, Karen N. Gregorczyk, Carolyn K. Bensel, Leif Hasselquist, John P. Obusek, and Louis Piscitelle
U.S. Army Natick Soldier Center, Natick, MA, 01760, USA

ABSTRACT

The purpose of the study was to investigate the effects of using a lower body prototype exoskeleton (EXO) on Soldiers' static limits of stability and postural sway. Ten Army enlisted men participated in the study. Limits of stability and postural sway were measured while participants stood on a force platform. Soldiers were tested with and without the EXO (15 kg) while carrying three load configurations: fighting load (20 kg), approach march load (40 kg), and emergency approach march load (55 kg). Body lean to the left and right was significantly less and postural sway excursions and maximal range of movement were significantly reduced when the EXO was used. Hurst values indicated that body sway was less random over short-term time intervals and more random over long-term time intervals with the EXO than without it. The use of an EXO prototype changes both the individual's limits of stability and postural sway.

1. INTRODUCTION

Excessive loads continue to burden the dismounted Soldier. A survey of the load weights being carried by infantry troops during operations in Afghanistan reported that, for 48- to 72-h missions, approach march loads in excess of 45 kg (100 lbs) were carried by Soldiers in some squad positions (Task Force Devil Combined Arms Assessment Team, 2003). Carrying heavy backpack loads may contribute to poor balance, resulting in falls when Soldiers perform marches, negotiate obstacles, and maneuver in operations. Falling may result in inefficient performance, in injury, and time lost from duty (Army Medical Surveillance Activity, 2001; Senier et al., 2002). Studies of balance while standing suggest that carrying a load affects the body's equilibrium and stability limits (Holbein and Redfern, 1997; Schiffman et al., 2006). Improving balance during load carriage may be one area that can be targeted to improve Soldier performance. To enhance performance and reduce injury to the Soldier, the Army is continually striving to reduce the weight of the load a Soldier must carry without compromising the Soldier's safety as well as mission needs.

One approach that has been taken to alleviate the effects of load bearing is to employ an assistive device, such as a lower extremity exoskeleton (EXO) to augment human performance. A prototype EXO has been privately developed that consists of: a hip structure with a back plate to which a backpack is attached; tubular leg struts, which parallel the lateral surfaces of the wearer's legs and have joints at the hip, knee and ankle; and semi-rigid foot plates, which have bindings for securing the user's shod feet and contain sensors that monitor contact with the ground. The prototype EXO off-loads a portion of the vertical component of the carried load from the human, through the device, to the ground.

Little is known about the extent to which wearing a lower body exoskeleton load carriage assistive device affects balance. The EXO off-loads a portion of the vertical component of the carried load from the human. It does not produce any additional torque to raise a load against gravity. The user alone must control the moment of inertia of the load carried. The combined center of mass of the user, EXO, and load must be positioned over the base of support of the user plus EXO. Thus, the user, while wearing the device with a load, must adopt a forward leaning posture, similar to the normal postural adjustment assumed while carrying heavy loads.

Given that an exoskeleton for bearing loads is a fairly new technology, it remains unknown the extent to which carrying an external load with an EXO prototype affects balance. Few research studies have been done to assess the effects of carrying a rucksack load on control of balance. Balance is defined as the dynamics of body posture to prevent falling. Stability is generally defined as a person's ability to maintain or restore the equilibrium state of upright stance, without changing the base of support (Maki et al., 1990). It can be assessed as the maximal amount of body lean while standing or as the amount of postural sway, an indicator of the displacement of the center of mass relative to the base of support.

Limits of stability testing is a method that has been used to quantify whole body lean. Stabilography has been used to quantify postural sway. The methods involve the measurement of the center of pressure (COP) location of the ground reaction forces to identify leaning and sway, while individuals are in a standing posture. The COP represents the combined outcome of postural control: It is the vertical projection onto the base of support of the whole-body center of mass (Duarte et al., 2000).

1.1 Effects of Loads on Balance

Studies have found that the carrying of loads affects limits of stability. Holbein and Redfern (1997) examined

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 NOV 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **The Effects Of A Lower Body Exoskeleton Load Carriage Assistive Device On Limits Of Stability And Postural Sway**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Natick Soldier Center, Natick, MA, 01760, USA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM002075., The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

the stability limits of individuals holding loads in different positions. While maintaining a comfortable stance, with feet approximately hip width apart, subjects were handed a load and asked to lean forward, backward, right and left as far as possible. Subjects were instructed to maintain that posture for 4 sec and were required to maintain full foot contact with the floor. They were instructed to keep their body rigid and only rotate about the ankles. The authors found that holding the weight low at the sides with one hand and with two hands frequently produced the largest stability ranges and holding the weight on the shoulder resulted in the smallest stability range. In a similar study examining the stability limits of individuals holding loads in different postures, Holbein and Chaffin (1997) found that the unloaded posture resulted in a greater stability range as compared to loaded postures and, of the loaded postures, keeping the loads low resulted in greater stability ranges than keeping them high.

Studies have found that the carrying loads of various masses differentially affects postural sway. Schiffman et al. (2006) measured postural sway during static standing of enlisted Army men carrying militarily relevant loads of 6.0, 16.0, and 40.0 kg. The authors found that center of pressure excursions increased linearly with increases in load mass. Ledin and Odkvist (1993) measured postural sway during standing in test participants without loads on the body and with lead weights placed on the chest and back that totaled 20% of a participant's body weight. They found an increase in anterior-posterior sway area with the added weight on the body.

Other research into the effects of load carrying on postural sway has examined the impacts of load weight variations and general equipment design parameters. Roberts et al. (1996) examined the effects of 13 different designs of load carriage equipment, all weighted with a 36.4-kg load, on postural sway before and after exercise. Prior to exercise, Roberts et al. found that the U.S. Marine study volunteers exhibited no differences in postural sway between the pack conditions and an unloaded condition. After exercise, the authors found that the Marines tended (no statistically significant differences) to have decreased sway with those packs designed to distribute weight to the shoulders, as opposed to the hips. Other researchers found that internal-frame packs, as compared to external-frame designs, resulted in improved standing balance ability (i.e., less extensive sway) in men and women (Nelson and Martin, 1982). Punakallio et al. (2003) quantified the effects that firefighting protective clothing had on postural sway. The subjects swayed significantly more in both the anterior-posterior and the medio-lateral directions when wearing 26-kg of firefighting protective clothing and a self-contained breathing apparatus (SCBA) than when they were outfitted in athletic attire. Punakallio et al. maintained the SCBA (worn on the back) was the piece of protective equipment most responsible for the postural instability because it shifted the center of gravity higher on the body and posteriorly, compared with the unburdened condition, and its weight placed more strain on the postural control system. From these studies of postural stability, it appears that the carrying of large loads affects postural sway and that how loads are carried on the body (load position or load bearing equipment) may be related to balance. However, it remains unknown how a load carriage assistive device, such as a lower body exoskeleton, may affect balance.

1.2 Stochastic Model for Analysis of Postural Sway

In the studies of postural sway as affected by the carrying of loads, COP excursion length and area have been the variables that have traditionally been examined. These measures relate to the movement of the body's COM relative to the base of support. However, Collins and De Luca (1993) asserted that the dynamic characteristics of the COP time series data provide important insights into postural sway that are not seen when only the anterior-posterior or medio-lateral displacement of the COP relative to the body's base of support is investigated. Collins and De Luca postulated that "the movement of the COP during quiet standing can be modeled as a system of coupled, correlated random walks, i.e., the motion is considered to be the result of a combination of deterministic and stochastic mechanisms." Collins and De Luca proposed that COP trajectories be analyzed and interpreted using a general stochastic model, which they referred to as stabilogram-diffusion analysis (SDA), in order to help explain the strategies used by the postural control system to maintain equilibrium during quiet standing. The mean square displacements of COP against time are determined to obtain a stabilogram-diffusion plot.

From a random-walk analysis, a number of parameters can be determined (Collins and De Luca, 1993). The parameter of interest in this study was the Hurst scaling exponent ($0 < H < 1$), a dimensionless measure that is the ratio of a range of cumulative fluctuations and time intervals observed. A Hurst value of 0.5 describes the classical Brownian movement and characterizes random motion. A value greater than 0.5 is associated with the short-term dynamics of the open-loop postural control mechanisms and describes postural instability by reflecting a tendency for postural sway to drift away from an equilibrium point in the short term. A Hurst value less than 0.5 is associated with the long-term dynamics of the closed-loop control mechanisms and describes greater control being exercised for postural stability over the long term, with movements away from equilibrium being offset by corrective adjustments back toward the equilibrium position. Thus, according to Collins and De Luca, the COP tends to move away from some equilibrium point during short-term intervals and tends to return to a relative equilibrium point over longer-term intervals. The change from open-loop to closed-loop control of standing posture is denoted by the critical point, which is a change in slope of the stabilogram. Thus, two distinct postural control patterns emerge and are utilized: an open-loop control scheme over the short term and a closed-loop control scheme over the long term.

Recently, Schiffman et al. (2006) reported on the results of measuring postural sway using this stochastic model. In the study, Army enlisted men stood while carrying military loads of 6.0, 16.0, and 40.0 kg. Schiffman et al. asserted that increasing load weight increased the tendency for COP to move away from some equilibrium point over the short term and reduced the randomness of postural sway over the long term, requiring the load carriers to exert greater control of the load in order to maintain balance. Investigating the effects of a lower body EXO load carriage assistive device on COP trajectories of Soldiers using these methods may yield important information about how an EXO affects the open- and closed-loop patterns of postural control.

1.3 Purpose of Study

The purpose of the study was to investigate the effects of using a prototype EXO on Soldiers' static limits of stability and postural sway. We tested the effects of using an EXO versus No-EXO across a range of load weights: 20, 40, and 55 kg. It was hypothesized that the limits of static stability would change while wearing the EXO as compared to not wearing the EXO under identical load conditions. It was also hypothesized that postural sway while wearing the EXO would reveal a change in COP excursions and a change in random behavior as compared to not wearing the EXO.

2. METHODS

Table 1. Means (and SDs) of Volunteers' Characteristics

Age (yr)	21.1	(3.70)
Height (m)	1.76	(0.05)
Weight (kg)	75.34	(9.28)

Ten Army enlisted men took part in the study (Table 1). Informed consent was obtained and the study was approved by the IRB and conducted in accordance with Federal Policy for the Protection of Human Subjects, Department of Defense, 32 CFR Part 219. The participants had completed infantry basic and advanced training and were awaiting their first assignments to operational Army units. All volunteers were healthy and without musculoskeletal injuries or disorders.

2.1 Load Conditions

We tested the Soldiers with and without wearing the EXO prototype (15 kg) under three load weight configurations comprised of Army clothing and equipment: fighting load (fighting, 20 kg), approach march load (approach, 40 kg), and emergency approach march load (emergency, 55 kg) (Fig. 1.). In all configurations, the Soldiers carried a molded plastic training M4 rifle at the ready position and wore a basic outfit consisting of combat boots, socks, T-shirt, and warm-up pants. The fighting load consisted of the basic outfit plus a helmet, an armor vest, and a cloth vest with pouches on the front (a MOLLE Fighting Load Carrier). The pouches contained a canteen filled with water, dummy grenades, and dummy ammunition. The approach march and emergency approach march loads consisted of the fighting load plus a backpack (a MOLLE Rucksack and Frame) loaded with a mass of 20 kg and 35 kg, respectively. Common Soldier items were placed inside and attached to the outside of the backpack to attain the desired weights. The backpack loads were configured such that the center of mass (COM) was approximately 0.22 m away from the back of the wearer and 0.25 m up from the hips of the wearer, a COM position that comports to COM locations in standard Army combat loads (Hasselquist et al., 2004).

Fig. 1. Soldier wearing EXO prototype and emergency approach march load, while standing on force plate

2.2 Experimental Procedures

Prior to testing, the foot placement that would be used throughout the study was established for each volunteer. A volunteer, outfitted in the EXO and fighting load, stood on a sheet of paper (0.76 m x 0.46 m) in a relaxed posture, eyes focused straight ahead, and weight evenly distributed on both feet. The position of each foot was marked on the paper. Each volunteer's recorded foot positions were then used during all limits of stability and postural sway testing. We measured the marked locations to obtain stance width and stance angle (McIlroy and Maki, 1997), which averaged 0.27 m (SD 0.03) and 13 deg (SD 10.3), respectively.

Postural sway testing preceded limits of stability testing. For both tests, a volunteer stood on a force plate, with the feet set according to the recorded position, and held a mock M4 rifle in both hands (Fig. 1). The order in which the Soldiers wore the EXO or No-EXO was counterbalanced. Within each test, half of the volunteers wore the EXO for all loads first, while the other half wore No-EXO first. The order in which the Soldiers were exposed to the three load configurations was based on a Latin square.

For the limits of stability (LOS) testing, volunteers were told to lean as far as possible in one of four directions (forward, backward, left, or right). The order of exposure to the directions was based on a quasi-Latin square. Volunteers were instructed to keep their body rigid above the ankles and to maintain full foot contact with the force plate. Once set, volunteers maintained their leaning position for 3 seconds while center of pressure data were collected. The volunteers then returned to their normal stance posture for several seconds before performing two more trials in the same direction. This procedure was repeated until three successive trials in each direction were completed for each load with the EXO on and without it.

For the postural sway testing, the Soldiers stood looking straight ahead, in a comfortable and relaxed position on the force plate. Testing of a load consisted of 5 successive, 30-s trials of standing in place. Five trials were conducted for each load with the EXO and without it. A 45-s break was provided after every two trials.

2.3 Data Recording and Processing

Kinetic data were collected using an 800 x 400 mm force plate (MODEL OR6-5, AMTI, Inc., Watertown, MA, 907-kg Fz capacity) interfaced with a data acquisition system. Data were collected with a microcomputer running LabVIEW 6i with a data acquisition board (National Instruments, Austin, TX). The voltage output from the force plate was sampled at 100 Hz. For the traditional measures of center of pressure, the force plate output was filtered with a low-pass Butterworth filter (cut-off frequency of 10 Hz) and converted to physical units (N and N·m), eliminating phase shift using forward and backward passes.

The LOS measures included anterior-posterior static limits of stability (LOS_{AP}) and medio-lateral (left-right) static limits of stability (LOS_{ML}). Both were defined as the difference between the maximum 95th percentile COP locations for the forward (left) lean trials and the minimum 5th percentile COP locations for the backward (right) lean trials. Analysis techniques have been described thoroughly elsewhere (Owings et al., 2000).

The traditional measures of postural sway included total excursion lengths for the center of pressure (COP) paths in the X and the Y directions, designated as COP_{LX} and COP_{LY}, respectively. In this study, COP_{LX} corresponded to the anterior-posterior (AP) COP time series and COP_{LY} corresponded to the medio-lateral (ML) time series. The variable COP_{LR} was the resultant planar motion. Sway area, the total boundary of the COP designated as COP_B, was calculated by determining the maximum range of movement in the X (COP_{BX}) and in the Y (COP_{BY}) directions and then multiplying the two, which yielded the largest area containing the COP trace (Prieto et al., 1996). Larger boundary values and larger excursion values indicate greater sway.

To apply the SDA approach to the sway data, mean square COP displacement versus time interval curves were computed to obtain log-log plots of the trial period, with the plots being composed of short-term and long-term time interval regions. Scaling exponents were then calculated from the slopes of the plots for the short-term (Hxs, Hys, Hrs) and the long-term (Hxl, Hyl, Hrl) regions (Collins and De Luca, 1993), where 'x', 'y', and 'r' denote anterior-posterior, medio-lateral, and planar movements, respectively. These exponents elucidated upon the change in structure of postural sway as a function of EXO being worn and load condition. The short-term region refers to the first region of the stabilogram-diffusion plot, which extends from time interval of 0 s to time interval of 1.1 s, on average, for this data set. The long-term region refers to the remainder of the diffusion plot, from time interval of 1.1 s to time interval of 10 s. Classical Brownian motion, H, equals 0.5. Values less than 0.5 indicate anti-persistence; increasing (decreasing) trends in the past that imply decreasing (increasing) trends in the future, i.e., negatively correlated. Values greater than 0.5 indicate persistence; increasing (decreasing) trends in the past that imply increasing (decreasing) trends in the future, i.e., positively correlated.

2.4 Statistical Analysis

All statistical analyses were accomplished using SPSS 13.0. For all data, each dependent measure was calculated for a trial and then averaged over trials for a given test condition. A two-factor repeated measures analysis of variance (No-EXO/EXO, three load configurations) was run on each of the LOS measures, the traditional postural sway measures (COP_{BX}, COP_{BY} COP_B, COP_{LX}, COP_{LY}, COP_{LR}), and on the six Hurst exponents. In analyses in which the sphericity assumption was not met, the Greenhouse-Geisser adjustment was applied to the degrees of freedom. Alpha was set at .05 and significant findings were corrected for multiple comparisons using a step-up sequential Bonferroni procedure (Hommel, 1989). A significant ANOVA finding was followed up with post-hoc tests when appropriate.

3. RESULTS

Means and standard deviations for the LOS and postural sway measures are included in Tables 2 and 3, respectively. The summary data for each of the Hurst exponents are in Table 4.

Table 2. Means (and Standard Deviations) for LOS Measures for EXO/No-EXO and Each Load (*N* =10)

Variable	Load	EXO	No-EXO
LOS_{AP} (cm)	Fighting	14.88 (2.55)	14.60 (1.76)
	Approach	14.30 (2.81)	14.34 (1.93)
	Emergency	14.35 (1.82)	14.53 (2.44)
LOS_{ML} (cm)	Fighting	26.00 (4.46)	30.75 (2.87)
	Approach	23.65 (5.73)	30.52 (2.96)
	Emergency	24.83 (4.90)	30.71 (3.16)

Note. Larger values indicate greater leaning limits of stability.

Table 3. Means and (Standard Deviations) for Postural Sway Measures for EXO/No-EXO and Each Load (*N* =10)

Variable	Load	EXO	No-EXO
COP_{BX} (cm)	Fighting	2.44 (1.01)	2.96 (0.96)
	Approach	2.91 (1.19)	3.83 (1.36)
	Emergency	3.34 (0.95)	4.24 (1.65)
COP_{BY} (cm)	Fighting	0.84 (0.40)	1.34 (0.48)
	Approach	0.92 (0.53)	1.70 (0.78)
	Emergency	0.96 (0.43)	2.54 (1.09)
COP_B (cm^2)	Fighting	2.50 (2.06)	4.38 (3.04)
	Approach	3.28 (3.08)	7.31 (5.69)
	Emergency	3.68 (2.31)	12.66 (9.43)
COP_{LX} (cm)	Fighting	20.21 (5.60)	29.05 (7.66)
	Approach	22.30 (5.97)	34.78 (8.62)
	Emergency	24.39 (3.54)	39.49 (12.92)
COP_{LY} (cm)	Fighting	17.07 (4.10)	15.66 (4.47)
	Approach	18.89 (5.83)	19.99 (9.30)
	Emergency	21.45 (7.96)	26.68 (13.86)
COP_{LR} (cm)	Fighting	29.61 (7.11)	36.00 (9.24)
	Approach	32.66 (8.41)	44.16 (13.57)
	Emergency	36.46 (8.33)	52.94 (20.76)

Note. Larger values indicate greater sway.

3.1 Limits of Stability Results

For limits of stability testing (Table 2), LOS_{ML} was found to be significantly affected by the use of the EXO ($p < 0.05$). Using the EXO as compared to No-EXO resulted in significantly lower maximum lean to the left and right. No significant differences were found for LOS_{AP}. Further, no significant load effects or load x EXO interaction effects were found.

Table 4. Means (and Standard Deviations) for Hurst Exponents for EXO/No-EXO and Each Load (*N* =10)

Variable	Load	EXO	No-EXO
Hxs	Fighting	0.79 (0.04)	0.84 (0.05)
	Approach	0.81 (0.06)	0.83 (0.06)
	Emergency	0.81 (0.05)	0.84 (0.05)
Hxl	Fighting	0.35 (0.12)	0.17 (0.12)
	Approach	0.30 (0.10)	0.20 (0.11)
	Emergency	0.27 (0.14)	0.12 (0.11)
Hys	Fighting	0.89 (0.06)	0.81 (0.06)
	Approach	0.95 (0.04)	0.83 (0.04)
	Emergency	0.95 (0.03)	0.83 (0.04)
Hyl	Fighting	0.11 (0.09)	0.19 (0.08)
	Approach	0.06 (0.04)	0.15 (0.11)
	Emergency	0.07 (0.05)	0.09 (0.09)
Hrs	Fighting	0.80 (0.04)	0.80 (0.04)
	Approach	0.82 (0.05)	0.83 (0.05)
	Emergency	0.82 (0.04)	0.84 (0.05)
Hrl	Fighting	0.34 (0.10)	0.17 (0.11)
	Approach	0.29 (0.09)	0.20 (0.10)
	Emergency	0.27 (0.11)	0.11 (0.09)

Note. Values < 0.5 indicate a negatively correlated trend; values > 0.5 indicate a positively correlated trend.

3.2 Traditional Postural Sway Results

For postural sway (Table 3), after correcting for Type I Error, only COP_{BY} and COP_B yielded a significant interaction of EXO by load condition ($p < 0.05$). Follow-up paired t-tests found an EXO/No-EXO effect individually at each load for both dependent variables ($p <0.05$). The No-EXO condition consistently resulted in a greater maximum boundary in the medio-lateral direction and in total area. When considering only the No-EXO data for COP_{BY} and COP_B, a significant quadratic trend ($p < 0.05$) was found for load mass. Both COP_{BY} and COP_B increased as a function of load mass. However, no significant load mass trends were found when considering the EXO condition only.

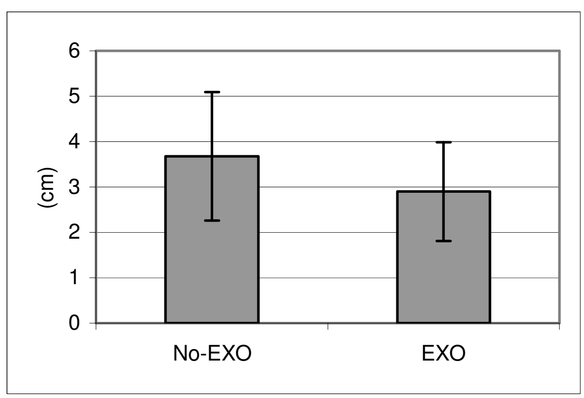

Fig. 2. Significant main effect of EXO/No-EXO for mean anterior-posterior boundary of COP (COP_{BX}). Error bars indicate 1 SD.

With regard to the main effect of EXO/No-EXO, all measures except COP_{Ly} were found to be significantly affected by the EXO ($p < 0.05$). For COP_{BX}, COP_{LX}, and COP_{LR}, the No-EXO condition consistently resulted in greater sway values compared to the EXO condition (Figs. 2 and 3). All sway measures except COP_{LR} were significantly affected by the load variable ($p < 0.05$).

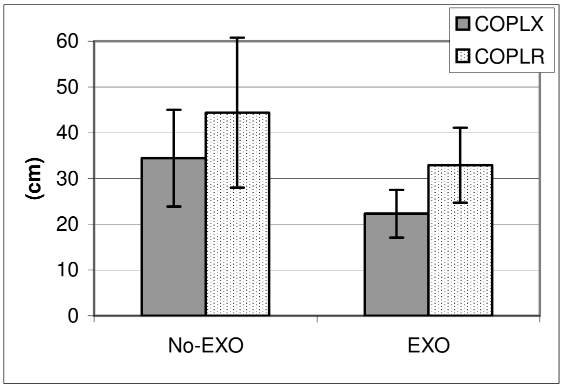

Fig. 3. Significant main effect of EXO/No-EXO for mean anterior-posterior and resultant excursion length of COP. Error bars indicate 1 SD.

3.3 Stochastic Analysis Results

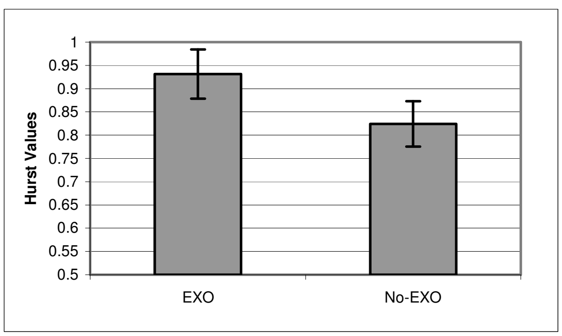

Fig. 4. Significant main effect of EXO/ No-EXO for mean short-term time interval exponent Hys. Error bars indicate 1 SD.

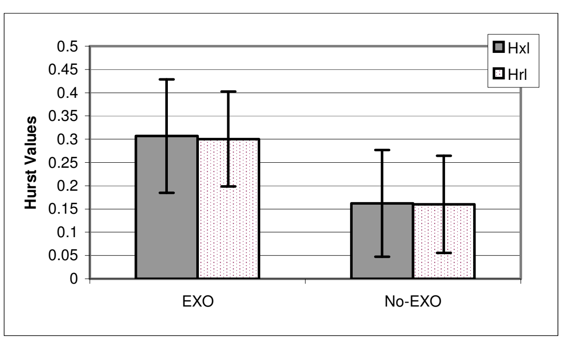

Fig. 5. Significant main effect of EXO/No-EXO for mean long-term time interval exponents Hxl and Hrl. Error bars indicate 1 SD.

The ANOVAs revealed no significant EXO by load interactions for any of the Hurst exponents. Hys, Hxl, and Hrl were significantly affected by the EXO versus No-EXO ($p < 0.05$). For Hys, the EXO resulted in more structured persistent sway (Fig. 4). For Hxl and Hrl, the EXO as compared to No-EXO, resulted in more random, less structured anti-persistent sway (Fig. 5). Further, only two of the six Hurst exponents were significantly affected by load ($p < 0.05$): These were Hys and Hyl. For both of these variables, the fighting load as compared to the other two loads yielded greater random behavior. With an increase in mass, both heavier loads demonstrated an increased persistent behavior over the short-term time intervals and an increased anti-persistence over the long-term time intervals.

4. DISCUSSION

The limits of stability analyses indicated that the maximum extent of body lean to the left and right was significantly less with the EXO than without it. It is likely that this finding is attributable to the EXO legs and feet, which provide a lateral brace to the user's limbs and a wide, semi-rigid standing surface under the user's feet.

The LOS analyses also indicated that the extent of body lean forwards and backwards was no different with the EXO than without it. This finding may be attributable primarily to the fact that, in the EXO, the user still had to exert control of the fighting load and the backpack in the AP direction to maintain balance. Further, the EXO was designed with bracing on the lateral sides of the body only to avoid restriction of anterior-posterior mobility, particularly restriction of knee and ankle movements.

The LOS data did not reveal any load effects or load x EXO interactions that were significant. Previous research found that holding loads in different postures vs. holding no load reduced limits of stability (Holbein and Chaffin, 1997). However, the current study did not include an unloaded condition. Whether carrying a load mass of 16 kg or 55 kg, the volunteers' limits of stability (in both directions) were unchanged.

Comparisons of postural sway with and without the EXO revealed that, at every load configuration, total sway area and sway boundary in the ML direction were significantly reduced when the EXO was used. Further, collapsed over all load weights, excursion lengths in the AP direction, planar motion, and maximum ranges of movement in the AP direction were significantly reduced when the EXO was used. Only ML excursion length was unaffected by the use of the EXO. As mentioned with regard to the LOS data, the lateral bracing provided by the EXO likely also limited the bounded sway area and excursion of the COP in the medio-lateral direction.

The sway data reveal that, for the EXO x load interaction, the use of the EXO diminished some postural sway responses associated with an increase in load seen when an EXO was not worn. Specifically, with the EXO, there were no significant load mass trends found for sway area or for ML excursion. In considering the No-EXO conditions alone, load mass increases yielded a significant trend of increases in sway area and ML excursion. This is in agreement with our previous work (Schiffman et al., 2006): We reported increases in sway area and excursion with increasing load mass. In the present study, the mean values for sway we obtained when the EXO was not used are similar to those we obtained in earlier research. The remaining sway variables, sway area in the AP direction and excursion length in the ML and AP directions, increased with increases in load weight, regardless of whether or not the EXO device was being worn.

In considering the effects of using an EXO on postural sway, it is possible that the semi-rigid surface under the EXO users' feet reduced proprioceptive sensory cues, which then affected sway features such as excursion or area. Contrary to this hypothesis, Priplata et al. (2006) found that enhancing sensorimotor function at the feet through vibrating insoles improved postural sway, as defined by reducing sway area and excursions. Based on those findings, one might expect a semi-rigid surface under the feet to increase sway area or excursion due to reduced sensorimotor function. However, the use of the EXO resulted in the opposite effect upon sway measures. It may be more likely the lateral bracing effect of the EXO contributed to the reduction in sway parameters by "locking down" the user to the ground and thereby reduced sway area and excursion (despite an increase in load mass). Further, the EXO, in supporting the vertical component of the load, may have prevented the increases in postural sway parameters normally associated with increases in the mass of the load carried on the body.

With the apparent increased standing stability, combined with the reduced medio-lateral stability limits during leaning, it is unclear how a user wearing this EXO may respond to dynamic balance scenarios. When walking, for example, it is possible that the amount of vertical force taken up by the EXO could be applied back to the wearer as trunk lean angle changes, thereby increasing the balance demand upon the user.

Although the extent of sway was reduced when the EXO was worn, the values of the Hurst exponents indicated that the body sway that did occur in the medio-lateral direction over short-term time intervals was less random with than without the EXO. In other words, over short-term time intervals, there was a tendency when wearing the EXO, for the user to sway away from an equilibrium point unchecked by the postural control system more so than when No-EXO was worn. Though the users swayed in a smaller boundary area medio-laterally with the EXO, their excursion length remained unchanged in this direction, most likely attributable to the fact that they had a tendency to drift away in the ML direction. It may be that the wearers of the EXO relied on the lateral bracing effect of the EXO to assist in stabilizing their bodies, which allowed their sway to persist more so for the short-term time intervals than when No-EXO was worn.

Over the long-term time intervals, Hurst exponents for the anterior-posterior and resultant directions indicated a greater randomness in sway when the EXO was used than when it was not. Without the EXO, volunteers had to make the postural adjustments necessary to control the load and to ensure their own stability: Any movements away from equilibrium had to be countered with movements back towards equilibrium. These findings are in agreement with our previous investigation of load weight effects upon postural sway structure (Schiffman, et al., 2006). Yet, when the EXO was worn, volunteers may have relied on the EXO to support the vertical component of the load and to provide added stability through the mechanical design that effectively yielded a lateral bracing effect.

When wearing the EXO, the drift away from equilibrium over short-term time intervals was not then offset by increased structure over long-term intervals, which Collins et al. (1995) suggested as one possible strategy to compensate for the effects of short-term drift away from equilibrium. This may indicate that users of the EXO relied on the device to provide a greater contribution to their overall stability. With the EXO supporting a portion of the vertical component of the load, volunteers may have relinquished some of their postural control over to the mechanical bracing of the EXO. Further, the inclusion of a semi-rigid footplate under the wearer's foot may have led to a loss of sensitivity under the foot and alteration in one's proprioceptive cues, thereby changing the structure of the sway to one of increased random activity. Priplata et al. (2006) recently demonstrated that randomly vibrating insoles decreased the values of Hrl in their test participants: Volunteers swayed less randomly when wearing the vibrating insoles. It may be that the foot interface of an EXO could be optimized to allow some direct contact between the user's shod foot and the floor surface, as opposed to having the foot portion of the EXO underlie the user's entire foot.

5. SUMMARY

The EXO prototype appeared to mitigate the effects of loads carried on traditional measures of postural sway. However, the EXO did reduce the limits of stability to the left and right and did alter the structure of sway such that the user was more likely to be moving away from equilibrium unchecked. The reduced sway and the relatively small changes in sway with increasing load weights suggest that the EXO structure may have functioned to provide a bracing effect to the user. Hurst exponents suggest that the user did not exert the same control to maintain postural stability when wearing the EXO: Feedback to the user's balance control mechanisms most likely was changed with the EXO. Additional research is needed to develop the fundamental understanding of how to optimize standing balance and dynamic stability for any exoskeleton design. At this time, findings from this study are not generalizeable across exoskeleton devices.

REFERENCES

Army Medical Surveillance Activity, 2001: *Injury Surveillance Through May 2001,* Aberdeen Proving Ground, MD: U.S. Army Center for Health Promotion and Preventive Medicine.

Collins, J.J., De Luca, C.J., Burrows, A., and Lipsitz, L.A., 1995: Age-related changes in open-loop and closed loop postural control mechanisms, *Exp. Brain Res.*, **104**, 480-492.

Collins, J.J., and De Luca, C.J., 1993: Open-loop and closed-loop control of posture: A random-walk analysis of center-of-pressure trajectories, *Exp. Brain Res.*, **95**, 308-318.

Duarte, M., Harvey, W., and Zatsiorsky, V. M., 2000: Stabilographic analysis of unconstrained standing. *Ergon*., **43**, 1824-1839.

Hasselquist, L., Bensel, C.K., Norton K., Piscitelle, L., and Schiffman, J.M., 2004: Characterizing center of mass and moment of inertia of soldiers' loads packed for combat. In: 24th Army Science Conference, Orlando FL.

Holbein, M. A., and Redfern, M. S., 1997: Functional stability limits while holding loads in various positions, *Int. J. Ind. Ergon.,* **19**, 387-395.

Holbein, M. A., and Chaffin, D. B., 1997: Stability limits in extreme postures: effect of load positioning, foot placement, and strength, *Hum. Fact,* **39**, 456-468.

Hommel, G., 1989: A comparison of two modified Bonferroni procedures, *Biometrika*, **76**, 624-625.

Ledin, T. and Odkvist, L.M., 1993: Effects of increased inertial load in dynamic and randomized perturbed posturography, *Acta. Otolaryngol.,* **113***,* 249 - 252.

Maki, B.E., Holliday, P.J., and Fernie, G.R., 1990: Ageing and postural control. A comparison of spontaneous- and induced-sway balance test, *J. Amer. Ger. Soc.,* **38***,* 1-9.

McIlroy, W.E. and Maki, B.E., 1997: Preferred placement of the feet during quiet stance: Development of a standardized foot placement for balance testing, *Clin. Biomech.,* **12***,* 66-70.

Nelson, R.C. and Martin, P.E., 1982: *Volume II. Effects of gender, load, and backpack on easy standing and vertical jump performance* (Tech. Rep. TR-82/016), Natick, MA: U.S. Army Natick Research and Development Laboratories.

Owings, T. M., Pavol, M. J., Foley, K. T., and Grabiner, M. D., 2000: Measures of postural stability are not predictors of recovery from large postural disturbances in healthy older adults, *J. Am. Ger. Soc.,* **48**, 42-50.

Prieto, T.E., Myklebust, J.B., Hoffman, R.G., Lovett, E.G., and Myklebust, B.M., 1996: Measures of postural steadiness: Differences between healthy young and elderly adults, *IEEE Trans. Biomed. Eng.,* **42**, 956-966.

Priplata, A.A., Patritti, B.L., Niemi, J.B., Hughes, R., Gravelle, D.C., Lipsitz, L.A., Veves, A., Stein, J., Bonato, P., Collins, J.J., 2006: Noise-enhanced balance control in patients with diabetes and patients with stroke, *Ann. Neurol*., **59**, 4-12.

Punakallio, A., Lusa, S., and Luukkonen, R., 2003: Protective equipment affects balance abilities differently in younger and older firefighters, *Aviat. Space Environ. Med,*. **74**, 1151-1156.

Roberts, D.E., Reading, J.E., Daley, J.L., Hodgdon, J.A., and Pozos, R.S., 1996: *A physiological and biomechanical evaluation of commercial load bearing ensembles for the U.S. Marine Corps* (Tech. Rep. 96-7), San Diego, CA: Naval Health Research Center.

Schiffman, J. M., Bensel, C. K., Hasselquist, L., Piscitelle, L., and Gregorczyk, K. N., 2006: Effects of carried weight on random motion and traditional measures of postural sway, *Appl. Ergon.,* **37**, 607-614.

Senier, L., Bell, N.S., Yore, M.M., Amoroso, P.J., 2002: Hospitalizations for fall-related injuries among active-duty Army soldiers, *Work*, **18**, 161-170.

Task Force Devil Combined Arms Assessment Team, (2003): *The modern warrior's combat load: Dismounted operations in Afghanistan* (Draft 8-14-2003). Fort Leavenworth, KS: U.S. Army Center for Army Lessons Learned.