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Strength and Balance Guided Posture Selection during a Battery Maintenance Task

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ABSTRACT

Posture selection during standing exertions is a complex process involving tradeoffs between muscle strength and balance. Bodyweight utilization reduces the amount of upper-body strength required to perform a high force push/pull exertion but shifts the center-of-gravity towards the limits of the functional stability region. Thus balance constraints limit the extent to which bodyweight can be used to generate push/pull forces. This paper examines a two-handed sagittal plane pulling exertion performed during a battery maintenance task on a member of the family of medium-sized tactical vehicles (FMTV). Percent capable strength predictions and functional balance capabilities were determined for various two-handed pulling postures using the University of Michigan's 3D Static Strength Prediction Program (3DSSPP). Through this simulation study, preferred postures that minimize joint torques while maintaining balance were identified. Such preferred postures are important in redesigning the vehicle for improved maintenance.

INTRODUCTION

Vehicle maintenance is an essential part of military operations. Maintenance tasks often require manual handling of materials characterized by high-force exertions. Overexertion is a principal concern for the battery maintenance task analyzed in this paper. Physical strength, balance maintenance, and experience are required to minimize the risk of injury when removing the 33.5 kg batteries from the FMTV (Figure 1) (Rider *et al*., 2004). Risk of injury is greatly increased when job strength requirements exceed worker capabilities (Chaffin *et al*., 1978) and over-exertion injuries are costly. Manual materials handling and jobs involving hand force application through tool use are responsible for approximately 45% of all industrial over-exertion injuries, resulting in $110 billion in annual compensation in the U.S. alone (Mital & Das, 1987).

Approximately half of all manual materials handling tasks consist of pushing and pulling exertions (Kumar *et al*., 1995). These tasks are of concern since low-back pain is associated with pushing and pulling, and a study regarding push/pull risk factors indicates that shoulder and upper extremity complaints are also likely related to pushing and pulling (Hoozemans *et al*., 1998). Specifically, the task of pulling the back battery to the front of the battery tray involves high pull-forces.

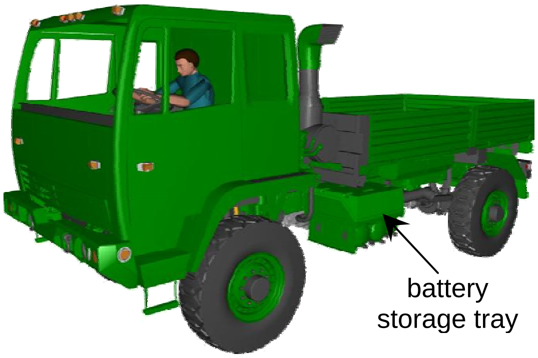


Figure 1. Digital representation of medium-sized military vehicle (FMTV) used in analysis.

Basic mechanics have been used to explain postural strategies commonly observed during pushing and pulling exertions. Gaughran and Dempster (1956) and Dempster (1958) measured maximal push and pull exertions in different postures and showed that the magnitude of the push/pull force one can exert is related to the relative magnitudes of the gravitational and horizontal force couples acting on the system (subject, seat/ground, force handle). These analyses illustrate how the condition of static equilibrium might be used to identify preferred pushing and pulling postures, along with appropriate muscle and body balance limits.

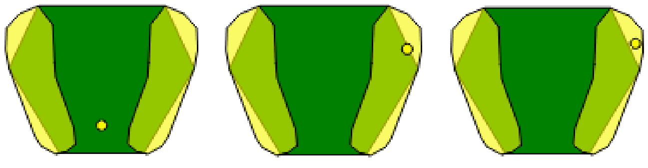
The objective of this paper was to identify preferred postures for an element of the battery maintenance task, the two-handed pull required to bring the back battery to the front of the battery tray (Figure 2). Task postures are constrained by the location, height and horizontal reach distance to the battery, and battery dimensions. Preferred postures are defined as feasible postures that minimize joint torques while maintaining balance. The interaction between postures and population joint strengths and balance capability can be analyzed using a strength prediction model to identify preferred postures for the task of interest.

Figure 2. Pulling the back battery to the front of the battery tray.

METHODS

The 3D Static Strength Prediction Program (Version 5.0.3) was used to conduct the simulation analysis. Given hand loads and a task posture, the model simultaneously evaluates joint muscle strengths and body balance for a specified population percentile. Strength is assessed by computing resultant joint torques and comparing these values to a set of regression equations which represent the strength capabilities of different populations. The model logic is further explained in the text by Chaffin et al. (1999).

Body balance is assessed in the 3DSSPP by computing the center-of-pressure (COP) and evaluating the location of the COP projected onto the floor with respect to the limits of the Functional Stability Region. These limits are based on balance studies conducted by Holbein and Chaffin (1997) and are a measure of how far a person can allow their COP to travel before losing their balance. The COP represents the point where the reactive force, resulting from displacement of the body's center-of-gravity and forces exerted at the hands, acts. Body balance is categorized as 'acceptable', 'critical', or 'unacceptable' by the 3DSSPP when the COP lies within, on the boundary, or outside the Functional Stability Region (Figure 3). A quantitative measure of balance is also provided in the form of the distance from the projected COP to the boundaries of the Functional Stability Region.



Acceptable Critical Unacceptable

Figure 3. Categorization of body balance as defined by the location of the projected COP with respect to the Functional Stability Region.

A pre-defined set of two-handed pulling postures was analyzed using the 3DSSPP for a 50%tile female and 95%tile male. An attempt to simulate a 5%tile (smaller and weaker) female revealed that the required hand locations could not be achieved for the majority of the postures selected for analysis. The set of feasible two-handed pulling postures analyzed are depicted in Figure 4. Postures were selected based on postural strategies observed during a push/pull pilot study and from a video of the battery maintenance task. Twenty-four postures were analyzed for both a 50%tile female and 95%tile male for a total of forty-eight simulations.

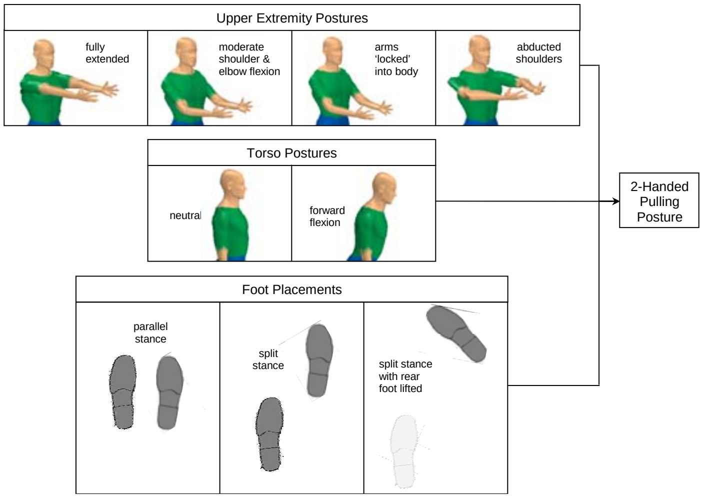


Figure 4. Set of feasible two-handed pulling postures analyzed. Postures are defined by all possible combinations of the above upper extremity postures, torso postures, and foot placements subject to task constraints.

The general procedure followed to perform the analysis for each two-handed pulling posture was as follows:

1. Set anthropometry to reflect 50%tile female or 95%tile male.
2. Enter a force of 98.75 N in each hand (see below for details).
3. Set the force direction by selecting 'pull back'.
4. Enter body segment angles for pre-defined upper extremity and torso postures.
5. Activate locking mode for arms and trunk to prevent alteration of the upper-extremity and torso postures when manipulating the lower-extremities.
6. Position lower extremities to achieve desired hand locations while maintaining balance and maximizing strength capability, if possible.
7. Modify upper-extremity posture to achieve desired hand locations as necessary.
8. Output graphics of final posture, standing balance and strength capabilities reports, and sagittal plane low-back analysis.
9. Remove hand loads to determine the location of the center-of-gravity of the body with respect to the base of support.
10. Output standing balance report for unloaded posture.

Hand locations were defined by CAD drawings of the FMTV battery and battery tray. The amount of force required to pull the 33.5 kg battery forward was estimated by assuming a static coefficient of friction of 0.6 (steel on steel). A force of 98.75 N per hand assumes the pull force is equally divided between the right and left hand.

The set of postural analyses obtained from the 3DSSPP were used to select the subset of postures which satisfied the following biomechanics-based criteria: (1) in static balance, (2) % capable prediction ≥ 90% for limiting joint, (3) low-back compression force < 3400 N. A posture ranking system was then applied to this subset of postures to identify preferred two-handed pulling postures for both a 50%tile female and 95%tile male. Rankings were assigned based on the percent capable strength prediction for the limiting joint(s), low-back compression force, and minimum distance from the projected COP to the Functional Stability Region boundary. The posture with the highest ranking was identified as the preferred posture. Figure 5 illustrates the steps outlined above by which preferred postures were determined.

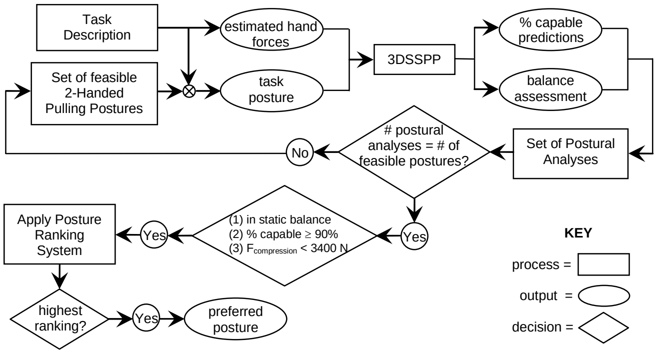


Figure 5. Flow diagram of simulation study to determine preferred two-handed pulling postures.

A sensitivity analysis was performed to quantify the effect of hand force magnitude and direction on strength, low-back, and balance analyses for the preferred postures (Figure 6). This analysis was performed to understand how assumptions regarding hand force magnitude and direction influence the results of this simulation study.

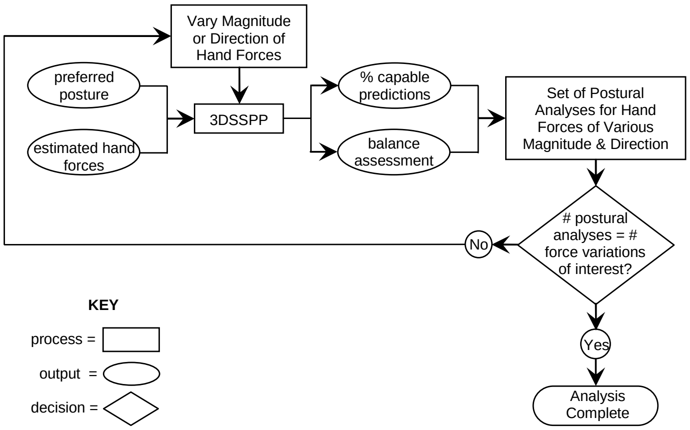


Figure 6. Flow diagram of sensitivity analysis performed on preferred two-handed pulling postures.

RESULTS

Preferred two-handed pulling postures for a 95%tile male and 50%tile female are depicted in Figure 7. Upper-extremity postures are categorically the same for the male and female preferred postures with differences in shoulder and elbow joint angles ranging from zero to seventeen degrees (Table 1). Differences in lower-extremity joint angles are larger ranging from five to fifty-one degrees (Table 2). The female posture is characterized by a greater amount of knee and ankle extension than the male posture.

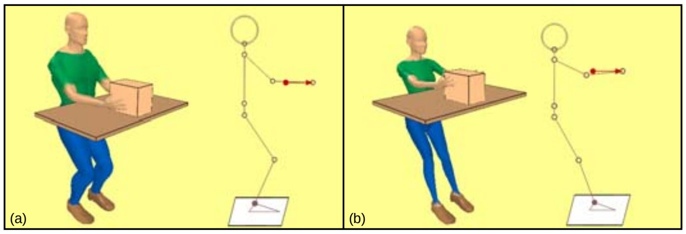


Figure 7. Preferred two-handed pulling postures for (a) 95%tile male and (b) 50%tile female.

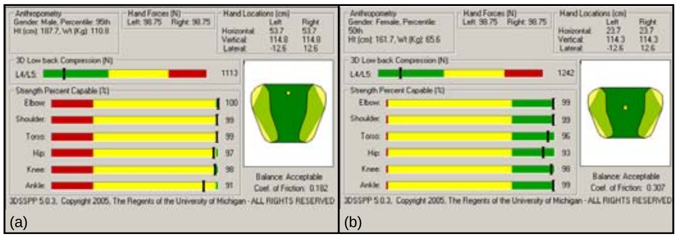
	Elbow Included	Shoulder Vertical	Shoulder Horizontal	Humeral Rotation	Torso Flexion
95%tile Male	139	48	90	15	89
50%tile Female	148	65	90	11	89
Difference	9	17	0	4	0

Table 1. Upper-extremity joint angles of preferred postures in degrees.

	Hip Included	Knee Included	Ankle Included
95%tile Male	145	120	65
50%tile Female	150	171	111
Difference	5	51	46

Table 2. Lower-extremity joint angles of preferred postures in degrees.

Analysis of the 95%tile male preferred posture (Figure 8a) indicates that 91% of this population has the strength required to perform the task with the ankle being the limiting joint. The hip is the limiting joint for the 50%tile female preferred posture with 93% of the population having the necessary strength (Figure 8b). Categorization of the body balance as ‘acceptable’ indicates that both postures are in static balance.


(a)

Anthropometry
Gender: Male, Percentile: 95th
Ht (cm): 187.7, Wt (Kg): 110.8

Hand Forces (N)
Left: 98.75 Right: 98.75

Hand Locations (cm)

	Left	Right
Horizontal	53.7	53.7
Vertical	114.8	114.8
Lateral	-12.6	12.6

3D Low back Compression (N)
L4/L5: 1113

Strength Percent Capable (%)

Elbow	100
Shoulder	99
Torso	99
Hip	97
Knee	98
Ankle	91

Balance: Acceptable
Coef. of Friction: 0.182

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(b)

Anthropometry
Gender: Female, Percentile: 50th
Ht (cm): 161.7, Wt (Kg): 65.6

Hand Forces (N)
Left: 98.75 Right: 98.75

Hand Locations (cm)

	Left	Right
Horizontal	23.7	23.7
Vertical	114.3	114.3
Lateral	-12.6	12.6

3D Low back Compression (N)
L4/L5: 1242

Strength Percent Capable (%)

Elbow	99
Shoulder	99
Torso	96
Hip	93
Knee	98
Ankle	99

Balance: Acceptable
Coef. of Friction: 0.307

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Figure 8. Analysis summary from 3DSSPP for (a) 95%tile male and (b) 50%tile female preferred postures.

The location of the body center-of-gravity with respect to the Functional Stability Region is provided by the body balance graphic when the posture is unloaded (Figure 9). In the absence of hand forces the male would remain in static balance while the female would tend to fall backward. This is indicated by the fact that the female's center-of-gravity lies rearward of her base of support, and thus a split-stance would be preferred by stronger women to avoid the risk of falling backward (Figure 9c).

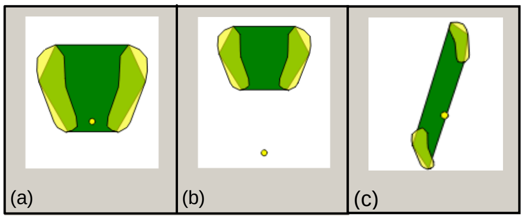

Figure 9. Body center-of-gravity location with respect to the Functional Stability Region for (a) 95%tile male and (b) 50%tile female preferred postures and for (c) a 50%tile female split-stance posture.

Results from the sensitivity analysis are summarized in Figure 10. Variations in percent capable strength prediction for the limiting joint(s), low-back compression force, and minimum distance to the boundary of the Functional Stability Region with force direction and magnitude are presented graphically. Force direction is specified by the angular deviation of the hand force vector from the horizontal with negative values indicating a downward component and positive values an upward component. Force magnitude is expressed as the amount of force exerted at each hand.

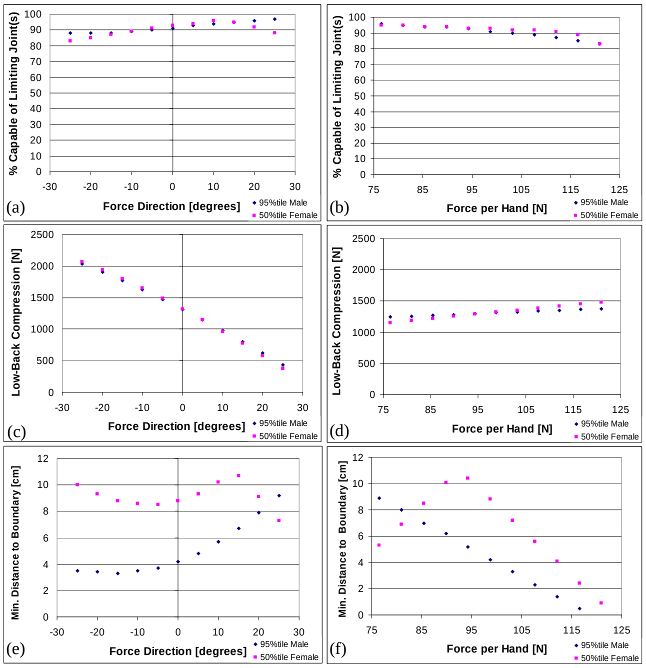

Figure 10. Variation in percent capable strength prediction for limiting joint(s) with force direction (a) and magnitude (b); variation in low-back compression force with force direction (c) and magnitude (d); variation in minimum distance to boundary of Functional Stability Region (FSR) with force direction (e) and magnitude (f).

DISCUSSION

Results from this simulation study suggest that task constraints, body balance, and lower-body strength are the principal determinants of preferred two-handed pulling postures. The requirement that each posture satisfy the specified hand locations resulted in anthropometry having a significant effect on posture selection. The influence of anthropometry on posture selection is illustrated by the differences in the preferred two-handed pulling postures for a 95%tile male and 50%tile female. Because of her smaller stature and body mass the preferred posture for an average size female is characterized by more extended upper and lower-extremity postures and a larger rearward displacement of the body center-of-gravity. Greater upper and lower-body extension is required to satisfy the hand locations and the large center-of-gravity displacement is necessary to generate the required hand forces. The preferred posture for the 50%tile female is more risky than that of the 95%tile male since the body center-of-gravity lies outside the base of support. In the event that the hand forces were removed the female would fall backwards whereas the male would maintain standing balance.

Upper-body strength, specifically shoulder strength, was hypothesized to be a significant determinant of preferred two-handed pulling postures. Results from this study do not support this hypothesis. Strength predictions for the shoulder indicated 99% capability for all twenty-four postures analyzed. Shoulder strength is perhaps not a limiting factor for the battery maintenance task analyzed since the battery is located between shoulder and hip height for both the 95%tile male and 50%tile female and push/pull capability is highest when the point of force application lies between these heights (Chaffin *et al*., 1983). Pulling forces at these heights tend to not produce large shoulder moments.

It was also hypothesized that preferred two-handed pulling postures would be characterized by a fore-aft split-stance. This hypothesis was suggested by the work of Holbein and Chaffin (1997) in which they showed that an increased separation of the feet in a given direction allows for greater displacement of the center-of-gravity in that direction without loss of balance. This finding suggests that a fore-aft split-stance may allow for greater body weight utilization making it preferential for high-force push/pull exertions. However, the 3DSSPP analyses of the feasible postures characterized by a split-stance showed a marked decrease in lower-body percent capable strength predictions with adoption of the fore-aft split-stance. This finding warrants further investigation into the analysis of split-stance postures using the 3DSSPP.

Results from the sensitivity analysis indicate that percent capable strength predictions are not significantly affected by variations in hand force magnitude or direction. Low-back compressive force was found to be more sensitive to changes in force direction than magnitude; however, for all variations in hand forces considered the low-back compressive force remained well below the NIOSH limit of 3400 N. The minimum distance to the boundary of the Functional Stability Region was also found to differ with variations in the hand forces. For the highest hand force considered balance became 'unacceptable' for the 95%tile male preferred posture but remained 'acceptable' for all other forces studied. In general, analyses of the preferred postures were found to be fairly robust to variations in hand force magnitude and direction; thus, assumptions regarding the required hand forces are not believed to have undue influence over the outcome of this simulation study.

It is clear from this study that postures identified as preferential by biomechanics-based criteria are not always obvious. Complex interactions between posture and strength and body balance make identifying preferred postures without the aid of a strength prediction model extremely difficult. Small changes in joint angles can greatly affect percent capable strength predictions impacting a person's ability to safely perform a task. For ergonomics analysts to accurately classify postures as acceptable or unacceptable they must carefully consider the interactions between posture, hand forces, and anthropometry demonstrated in this paper.

REFERENCES

1. Center for Ergonomics, Three Dimensional Static Strength Prediction Program (3DSSPP) V 5.0.3, The University of Michigan, Ann Arbor, MI (2005).
2. Chaffin, D.B., Anderson, G.B.J. and Martin, B.J. (1999) *Occupational Biomechanics* (3rd Edition), J. Wiley & Sons, New York, NY.
3. Chaffin, D.B., Andres, R.O. and Garg, A. (1983) "Volitional postures during maximal push/pull exertions in the sagittal plane," *Human Factors*, 25(5): 541-550.
4. Chaffin, D.B., Herrin, G.D. and Keyserling, W.M. (1978) "Pre-employment strength testing – updated position," *Journal of Occupational & Environmental Medicine*, 20(6): 403-408.
5. Dempster, W.T. (1958) "Analysis of two-handed pulls using free body diagrams," *Journal of Applied Physiology*, 13(3): 469-480.
6. Gaughran, G.R.L. and Dempster, W.T. (1956) "Force analysis of horizontal two-handed pushes and pulls in the sagittal plane," *Human Biology*, 28(1): 67-92.
7. Holbein, M.A. and Chaffin, D.B. (1997) "Stability limits in extreme postures: effects of load positioning, foot placement, and strength," *Human Factors*, 39(3): 456-468.
8. Hoozemans, M.J.M., van der Beek, A.J., *et al*. (1998) "Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors," *Ergonomics*, 41(6): 757-781.
9. Kumar, S., Narayan, Y., and Bacchus, C. (1995) "Symmetric and asymmetric two-handed pull-push strength of young adults," *Human Factors*, 37(4): 854-865.
10. Mital, A. and Das, B. (1987) "Human strengths and occupational safety," *Clinical Biomechanics*, 2: 97-106.
11. Rider, K.A., Chaffin, D.B., Foulke, J.A. and Nebel, K.J. (2004) "Analysis and redesign of battery handling using Jack™ and HUMOSIM motions," SAE Technical Paper 2004-01-2145, Warrendale, PA.

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