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Experimental Evaluation of Postural Stability Using Stepping Strategies During Industrial Tasks

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Abstract. Foot positioning has a significant impact on human body stability control when completing a manufacturing task. In classical Digital Human Models (DHM), the use of stepping strategies to generate stable postures relies on simplistic models, which generally locate the DHM center of mass (COM) at half distance between feet contact or limit the zero moment point (ZMP) projection within the base of support (BOS). Developing more comprehensive stepping models requires rigorous experimental studies to extract human movement coordination strategies during manufacturing tasks, which can be used to validate DHM models. The objective of this study is to develop an experimental test bench representing industrial conditions and to carry out experiments to provide these DHM models with parameters of postural stability. The assessed postural stability parameters in this study were the support length which is a variation of the step length, and the ZMP position with respect to the BOS. Results obtained from a pilot subject showed that the contralateral and ipsilateral legs move respectively to expand the BOS in the direction of ZMP displacement to maximize stability.

Keywords. Posture, Stability, Stepping, Zero Moment Point

1. Introduction

A common aspect digital human models (DHM) strive to improve is their autonomy to position the human manikin in a biomechanically plausible posture under specific task conditions. Currently, few models allow for semi-autonomous placement of the manikin in the simulated environment requiring manual interactions by the user to refine the final simulated postures [1,2]. For models simulating standing tasks, stability criteria are important to ensure the generation of biomechanically plausible postures. In industrial conditions, the use of stepping to maintain a stable posture is frequent as workers will often need to reach or apply forces when accomplishing tasks [3].

Classical DHMs that utilize stepping behaviors to generate stable postures rely on simplistic models, which generally locate the DHMs center of mass (COM) at half distance between the feet contact position [4]. Predictive stepping models use experimentally collected data and calculations to predict data-based feet placement.

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These models rely on regression equations with the task characteristics as the inputs to position the manikin's feet [3,5,6]. They can predict transition stepping, but pose some challenges when simulating more complex asymmetrical handling or tool manipulation tasks with task parameters different from the experimentally collected data.

Optimization-based stepping models compute the feet position and posture through minimizing an objective function (e.g., joint torques) [7,8]. The main stability criterion for these models is accomplished by limiting the calculated zero moment point (ZMP) projection to stay inside the base of support (BOS), which is the convex hull of the feet contact points with the support plane. This basic formulation respects minimal stability requirements that maintain feet placement as long as stability is not compromised. The ZMP represents a virtual point where the total tilting moments generated from gravitational and external forces applied to the manikin are zero [9]. Although this method generates stepping according to external requirements, it has not yet been validated with suitable experimental data to verify if the feet placement is accurate.

This study is motivated by the Smart Posture Engine (SPE) technology to enhance the stability control of the DHM. The SPE is a posture prediction model used to generate biomechanically plausible final postures of a DHM given the simulated environment and the task information [10,11]. The SPE uses an inverse kinematics solver with selective filtering and prioritized constraints similar to Baerlocher [12] while avoiding the collision with the environment. The more recent stepping model proposed was developed as part of an improvement to the SPE [13]. The main stability difference in this model is that the ZMP and the feet placement are controlled more precisely with respect to the functional stability region, a smaller region than the BOS situated between feet contact. This allows the manikin to be simulated adopting the most stable posture possible depending on the required target reach, height, and loads. However, no experimental data has yet been produced to validate this concept.

In the literature, the majority of studies that have proposed foot positioning models studied general two-handed push-pull tasks [3,7,14], which is not representative of the observations found in the industrial field [15]. The study by Baril-Gingras and Lortie [15], conducted in industrial settings, allowed the identification of different postural strategies. Of the 944 material handling tasks observed, one-handed tasks and two-handed asymmetrical tasks represented respectively 55.4% and 35.6% of the handlings, which accounted for more than 90% of all evaluated handlings. This indicates that one-handed and out of sagittal plane tasks should be preferred when studying industrial tasks. In this same study, horizontal pushing and pulling (48.2%) was seen almost twice as often as vertical lifting and lowering (26.6%), where tasks accomplished with horizontal and transverse components were the most frequent. When reviewing the literature, accurate stepping behavior models derived from specific industrial task experiments providing human movement coordination are very scarce. No feet prediction model assessed tasks involving hand tools. Also, no study evaluated the effects of a transverse obstacle imposing spatial constraints and requiring subjects to execute tasks out of the sagittal plane without prescribing specific feet placement, which has been underlined by Wilkinson, Pinder, and Grieve [16] to require further investigation. Imposing specific feet position for out of sagittal plane tasks shows a strong indication that foot placement and posture constraints may have an important effect on force exertion capability [16,17,18]. Granata and Bennett [19] studied the effects of split and side-by-side stances on stability during pushing tasks, where stability was found to be significantly influenced by feet placement. In order for DHMs to become fully autonomous, the stepping prediction models need to be enhanced.

Although bracing and other postural strategies exist in the industrial field, this study focuses on maintaining stability through the stepping strategy, while executing tasks in different hand conditions, by limiting the use of other postural strategies. In this study, the subject is free to position their feet as wanted in order to adopt a preferred posture. Moreover, the use of a transverse obstacle requires the subject to execute the conditions without centering themself with respect to the line of the applied hand force. The use of a tool while completing the same tasks allows the evaluation of its influence on feet placement when compared to typical push and pull conditions. Because no previous study evaluated a transverse obstacle, the scaling of the target position was based on other scaled parameters found in the literature [18,19,20,21].

The primary objective of this study was to develop an experimental test bench that would allow the evaluation of the required parameters to assess the ZMP and human postural stability, such as the support length with respect to the BOS. It is hypothesized that during either centered tasks or tasks with a transverse obstacle, the contralateral and ipsilateral legs move respectively to expand the BOS in the direction of ZMP displacement in order to maximize the stability.

2. Method

2.1. The Conception of an Experimental Test Bench

A test bench was custom designed with two sliding rails mounted on articulated pantograph arms allowing the adjustment of a hand target position in all three axes and the addition of a transverse obstacle to impose spacial constraints for out of sagittal plane tasks (Figure 1). Lockable adjustments ensure no movement occurs during trials.

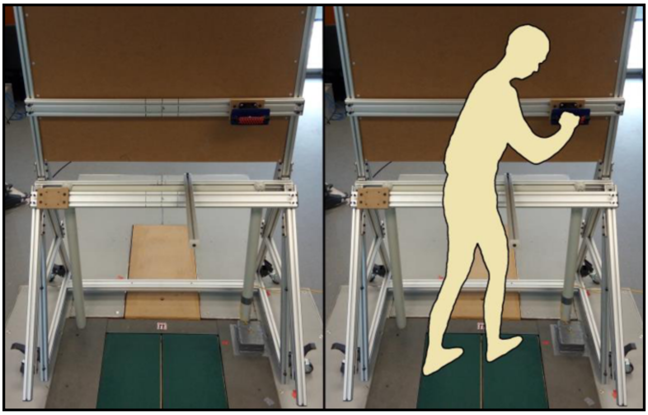


Figure 1. Experimental test bench positioned with a transverse obstacle.

For evaluating pushing and pulling, a 5 3/16" (131.7 mm) handle interface with a projection of 2" (50.8 mm) was built (Figure 2). It consists of a high-friction rubber handle with an anti-slip shape that enhances hand-handle grip. The second interface is for evaluating the use of a tool (Figure 2). Three reflective markers were fixed on each capture interface which is attached to a load cell and three other markers were affixed on the screwdriver, to locate their position in the environment.

2.2. Experimental Setup

Experiments were conducted in the Laboratoire de recherche en imagerie et orthopédie (LIO) of the Centre de recherche du Centre hospitalier de l'Université de Montréal (CRCHUM). Three synchronized acquisition systems were used to collect human kinematic data at a sampling frequency of 200 Hz and kinetic data at 1000 Hz (Figure 2): (1) AMTI MC3A 6-DOF load cell attached to the capture interface, (2) Twelve VICON MX T20-S motion capture cameras, and (3) ground force platforms. As shown in Figure 2, the experimental test bench is centered with the force platforms and is affixed in this position using anchor screws.

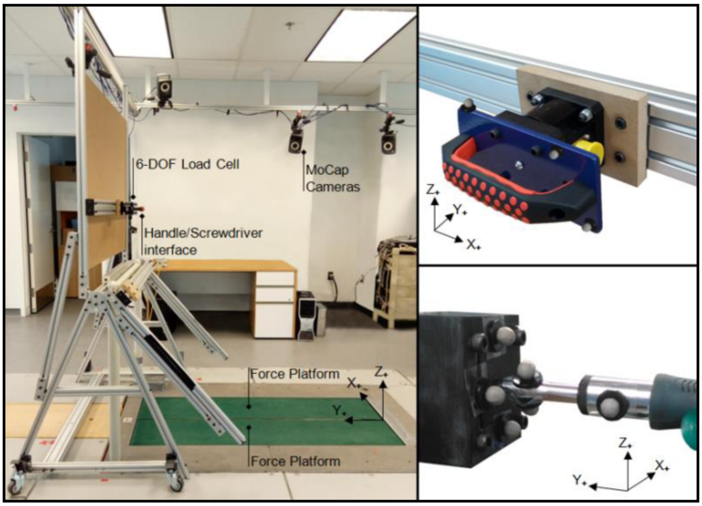


Figure 2. Experimental setup: Left, test bench affixed to the laboratory floor with acquisition systems. Right, two different capture interfaces developed. Pushing and pulling handle interface and screwdriver interface.

2.3. Pilot Subject

The subject assessed in this study was a right-hand dominant female with the following age, stature, weight, arm span, and hip-width: 24 years, 165 cm, 67 kg, 167 cm, and 31.12 cm, respectively. A total of 50 passive reflective markers were affixed on subject body landmarks as shown in Figure 3 [22].

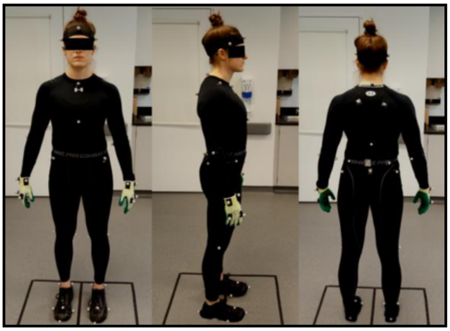


Figure 3. Passive reflective marker placement on the subject.

2.4. Experimental Procedure

Experiments were conducted with the right hand only, at an overhead position, and with two handle locations as presented in Table 1. For each handle locations, the subject performed four (4) task conditions. At least one practice trial of the presented target configuration was required to ensure that the preferred posture was adopted and that the subject was comfortable achieving the required force levels. For the transverse offset trials, the target was placed at 25% of the subject's arm span in X+ direction. The obstacle was fixed at the waist level and hip-width minus 5 cm transverse to the center of the force platforms. These positions were chosen to account for subject variability in arm span as well as anthropometric measurements that could influence reach and physical limitations in the experimental setup.

Table 1. Experimental protocol conditions and the number of trials analyzed.

Task Height	Handle location	Condition	Number of trials analyzed
Overhead	Centered	Reach	5
		Push	5
		Pull	5
		Tool	5
	Transverse offset	Reach	5
		Push	5
		Pull	5
		Tool	5

Experimental trials assessed in this study were conducted with a target height of 10 cm over stature (overhead), which was also studied by Hoffman et al. [21], as it is a position where the stepping strategy is isolated since the use of other postural stability strategies is limited. At this height, subjects won't favor the use of the squatting strategy as it will not benefit the vertical reach of the target. An overhead target has been seen to create more balance perturbation when leaning in a side-by-side stance and limit the use of body mass to increase applied hand force [16,18]. Although overhead work isn't a preferred working posture, it remains present in some industrial fields [23,24] and its study is important as it still represents a high impact risk from an ergonomic point of view [25,26].

The subject started facing the target with feet side-by-side outside of the posterior end of the force platforms. A verbal indication instructed the subject that the trial had started. The subject was required to take a few steps towards the target and adopt a preferred posture while, with their dominant hand, executing and maintaining for 5 seconds the required condition. After the specified time, another verbal indication was given, instructing the subject to stop and return to the start position. Audio feedback was produced once the minimum force of 40 N was obtained, announcing to the subject that the posture had to be maintained for at least 5 seconds. A different sound was produced if the maximum force exceeded 100 N, indicating to the subject to unload. For the tool condition using a screwdriver, the minimum required torque was 3 Nm and the maximum torque was 6.5 Nm [27]. Audio feedback was also produced once the minimal torque was achieved and if the maximal torque was exceeded.

2.5. Data Modeling

The body COM was calculated using the center of mass segmental distances presented by Dempster [22]. The individual adjusted segmental weight ratios presented by Clauser, McConville, and Young [28] were used. They were adjusted because the sum of Dempster's [22] ratios equaled 97.7% of total body mass. The body COM was estimated using a 14 segment model (Head, Trunk, Upper Arms, Forearms, Hands, Thighs, Tibias, and Feet) arising from individual marker position and subject mass.

The support length is the line passing through the projected points ML and MR, which are virtual points obtained from the intersection of the longitudinal axes (straight lines connecting the Phalanx Distal II and the heel) of the feet with the balance line [4]. The balance line is a line passing through the mean center of gravity (COG) during quiet standing and its direction is found by connecting the left and right mid malleolus. The COG is the vertical projection of the COM on the ground. Figure 4 illustrates this definition for our subject.

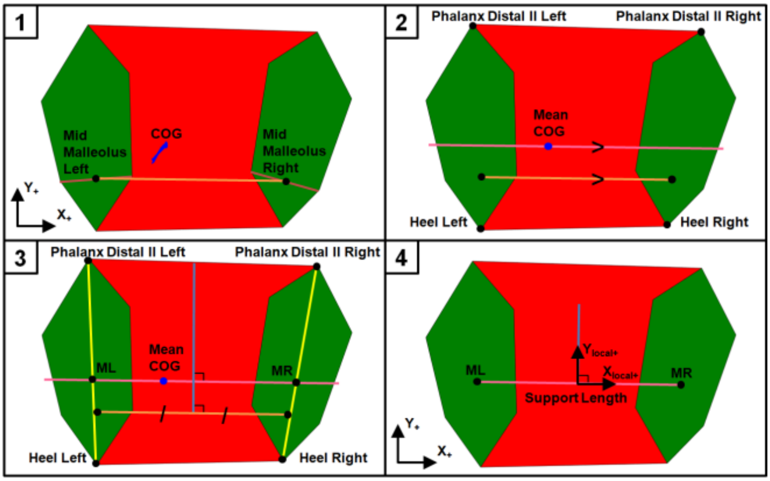


Figure 4. ML and MR points, support length, and local coordinate system definition during quiet standing.

Ground contact regions of the feet were estimated by comparing the vertical position of the feet markers against their vertical positions in the reference quiet standing trial. If a marker was 3 mm above the reference position, the part of the left or right foot was considered raised. The 3 mm threshold was set to account for possible variations (e.g., foot soft tissue deformation) [29].

3. Results

Marker position and kinetic data were low-pass filtered at specific cut-off frequencies (5-10 Hz, 4th order zero-lag Butterworth). Screwdriver weight was neglected because it was considered light enough and because pure torsion is applied directly in the center of the hand. It is considered that the tool COM nearly coincides with the hand COM which are both approximately in line with the applied moment as a diagonal volar grip is used with the screwdriver. The ZMP coordinates, defined by ZMP_X, ZMP_Y, and

ZMP_Z, were computed using Eq. (1) where X_{COG} and Y_{COG} are the COG coordinates, and f_bx, f_by, f_bz, M_bx, and M_by are the hand reaction forces and moments measured by the load cell [8]. The support surface is the ground, therefore ZMP_Z is set to 0. X, Y, and Z are the center coordinates of the capture interfaces and mg is the subject's weight.

$$\mathbf{ZMP_X} = \frac{(\mathbf{M_by} + \mathbf{f_bx} \times \mathbf{Z} - \mathbf{f_bz} \times \mathbf{X} + \mathbf{mg} \times \mathbf{X_{COG}})}{(\mathbf{mg} - \mathbf{f_bz})}$$

$$\mathbf{ZMP_Y} = \frac{(-\mathbf{M_bx} + \mathbf{f_by} \times \mathbf{Z} - \mathbf{f_bz} \times \mathbf{Y} + \mathbf{mg} \times \mathbf{Y_{COG}})}{(\mathbf{mg} - \mathbf{f_bz})}$$

$$\mathbf{ZMP_Z} = \mathbf{0} \tag{1}$$

After processing the raw data, parameters were obtained as illustrated in Figure 5. The BOS includes the left and right foot regions in contact with the ground as it is defined by the external polygonal line of the contact points between the feet with the ground. The D_2 ratio is a normalized ratio between 0.00 and 1.00 from the root foot (trailing leg), specified by the square projection of the mean 5-second static posture ZMP position (ZMP_X and ZMP_Y) on the support length. Consequently, if the D_2 ratio is superior to 1.00 the ZMP projection is situated outside of the support length.

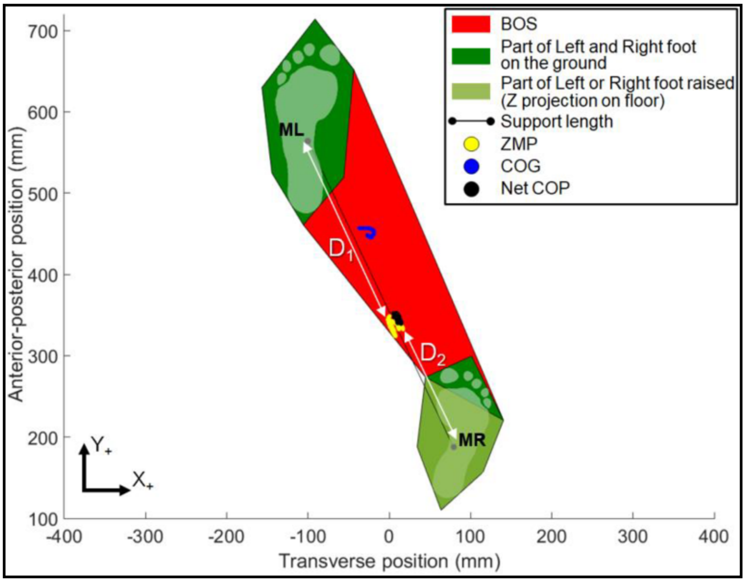


Figure 5. Processed trial parameters (XY plane projection) for a pushing centered trial.

Of the forty trials that were analyzed, one transverse offset-reach and one transverse offset-pull trials were removed from the analysis because bracing against the obstacle was seen in their video recording. Individual trial statistics of the calculated normalized D_2 ratio, the support length magnitude, and the occurrence of the dominant right foot being the lead foot are presented in Figure 6. The mean feet placement, the mean projected ZMP, and the mean projected COG on the support length for each condition and handle location are also illustrated. As hypothesized, the ipsilateral and contralateral legs moved accordingly to ensure the ZMP displacement remained collinear to the support length in the most stable direction. Across conditions requiring load exertions, the D_2 ratio varied in the direction of the hand reaction load. The ZMP and COG nearly coincide for the reach condition as no external force is present.

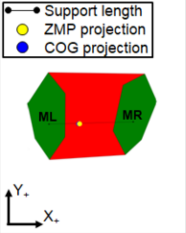
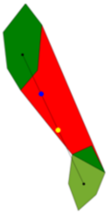
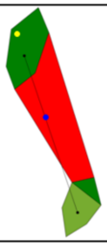
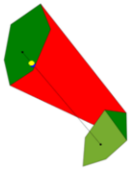
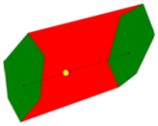
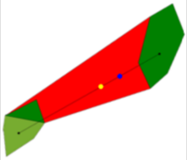
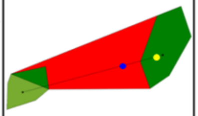
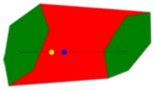
		Condition			
		Reach	Push	Pull	Tool
Handle location	**Centered**				
	D_2 ratio	0.65 (0.04)	0.42 (0.04)	1.11 (0.06)	0.88 (0.05)
	Support length magnitude (mm)	256.79 (10.15)	425.47 (34.98)	470.62 (32.68)	356.30 (30.35)
	Occurrence of right foot being lead foot	1/5	0/5	0/5	0/5
	Transverse offset				
	D_2 ratio	0.40 (0.05)	0.59 (0.06)	0.95 (0.04)	0.28 (0.06)
	Support length magnitude (mm)	317.38 (45.87)	418.32 (21.64)	403.59 (8.88)	325.30 (13.89)
	Occurrence of right foot being lead foot	4/4	5/5	4/4	5/5

Figure 6. ZMP projection in yellow and COG projection blue on the support length between ML and MR. Mean normalized (and standard deviations) D_2 ratio, support length magnitude, and lead foot occurrence across trials. Reference quiet standing trial support length of 250.73 mm.

Experimental trials also indicate that the projected COG is not predominantly located at half distance (0.50) between feet. The mean COG for each trial was found in a range varying from 0.40 to 0.86 normalized to the support length from the root foot.

4. Discussion

This study presents an experimental test bench capable of measuring hand forces and moments simultaneously with feet position when completing tasks in industrial conditions. It is noted that the sample size is limited, hence the conclusions remain partial. Ideally, subjects of different ages and anthropometry should be included to have an accurate representation of what is seen in the industrial field. Also, the number of tasks evaluated in this pilot study is limited, where variations of target position would allow the full integration of target parameters in a stepping prediction model.

Our exploratory experiments showed that task requirements vary the position of feet placement whether an obstacle is present or not. Over all trials, the subject moved the contralateral leg backward when the transverse obstacle was present, as feet were not constraint. During the centered trials, because the subject was able to center in line with the applied force direction, stability was maintained by expanding the BOS in the same direction as the applied force. These observations agree with Hoffman et al. [21], who stated that when possible subjects will prefer to position their body in line with the applied force direction to maximize applied forces by limiting lateral forces. During the transverse offset location trials, because the obstacle prevented the subject from positioning in line with the applied force, a more transverse feet placement strategy was used, possibly to develop sufficient torque at the foot base to compensate for the moment created by the hand force and the out of plane distance. This observation is consistent with Wilkinson et al. [16], where out of sagittal plane forces required the production of higher feet torque to ensure stability when standing with feet centered to the target. The mean support length appeared smaller for the transverse offset trials, which indicates hand-target reach might have been favored over stability.

These preliminary results indicate that feet placement varies according to task requirements, which will help validate the developed feet placement model for the SPE. In future works, it is intended to carry out an experimental protocol consisting of ten tasks varying in target height, reach, and obstacle. This protocol should be applied to a larger population size in order to develop a nonlinear regression model able to predict accurately the support length with respect to the ZMP position as well as its orientation about the target and the hand load requirements.

Acknowledgment

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