Gait & Posture 42 (2015) 430–434

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Effects of constrained arm swing on vertical center of mass displacement during walking

Hyung Suk Yang *, Lee T. Atkins, Daniel B. Jensen, C. Roger James

Center for Rehabilitation Research, Texas Tech University Health Science Center, TX, USA

ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form 9 July 2015
Accepted 13 July 2015

Keywords:
Gait
Ground reaction force
Kinematics
Energy

ABSTRACT

The purpose of this study was to determine the effects of constraining arm swing on the vertical displacement of the body's center of mass (COM) during treadmill walking and examine several common gait variables that may account for or mask differences in the body's COM motion with and without arm swing. Participants included 20 healthy individuals (10 male, 10 female; age: 27.8 $\pm$ 6.8 years). The body's COM displacement, first and second peak vertical ground reaction forces (VGRFs), and lowest VGRF during mid-stance, peak summed bilateral VGRF, lower extremity sagittal joint angles, stride length, and foot contact time were measured with and without arm swing during walking at 1.34 m/s. The body's COM displacement was greater with the arms constrained (arm swing: 4.1 $\pm$ 1.2 cm, arm constrained: 4.9 $\pm$ 1.2 cm, $p < 0.001$). Ground reaction force data indicated that the COM displacement increased in both double limb and single limb stance. However, kinematic patterns visually appeared similar between conditions. Shortened stride length and foot contact time also were observed, although these do not seem to account for the increased COM displacement. However, a change in arm COM acceleration might have contributed to the difference. These findings indicate that a change in arm swing causes differences in vertical COM displacement, which could increase energy expenditure.

1. Introduction

Humans swing their arms as they walk. Patterns of arm swing may change depending on the goals of walking. During normal walking the arms swing in opposition to the legs [1]. Arm swing partially arises from passive dynamics but active muscular control is also needed to control relative phase and amplitude [2]. Arm swing can influence gait stability and energy consumption. Several studies examined the effects of arm swing on gait stability. During steady state gait, Bruijn [3] and Collins [4] observed negative or no effects of arm swing on gait stability while other groups have reported increased trunk stability with excessive arm swing [5,6]. Balance recovery after a perturbation also may benefit from arm swing [7].

Studies also have reported decreased energy consumption with arm swing compared to constraining the arms [8,9]. It has been suggested that arm swing counteracts the angular momentum about the vertical axis and decreases vertical ground reaction moment [8,9]. Thus the stabilizing effects of arm swing could lead to a decrease in energy cost as a result of minimizing neuromuscular effort to maintain balance [9].

Increased vertical displacement of the COM has been suggested to increase energy expenditure [1]. Gordon et al. [10] argued that there may be an optimal vertical COM trajectory in terms of energy efficiency. Consequently, increased vertical displacement of the total body's COM beyond the optimal range may lead to an increase in energy expenditure in walking. However, COM movement should be viewed as a consequence of many other factors that humans use to minimize metabolic costs and it is not the COM displacement itself that is costing energy [10].

A few studies have examined the effect of arm swing on vertical displacement of the body's COM. Murray et al. [1] and Hinrichs [11] calculated theoretical COM movement of the arms relative to the rest of body's COM movement (referred to as body minus arms) during normal walking with arm swing. Both studies suggested that the total body's COM would be reduced with arm swing compared to constraining the arms because the vertical oscillation of the COM of the arms occurs in opposition to the vertical oscillation of the COM of the body minus the arms, resulting in a cancellation effect. However, their arguments were not tested in an experimental study with different arm swing conditions. Collins et al. [4] was the only previous study located that examined the

* Corresponding author. Tel.: +1 806 392 2220.
E-mail address: hs.yang@ttuhsc.edu (H.S. Yang).

http://dx.doi.org/10.1016/j.gaitpost.2015.07.010
0966-6362/

effect of arm swing on the body's COM with different arm swing conditions. Although their results exhibited a trend consistent with the theoretical prediction, they found no significant effects of arm constraint on vertical displacement of the COM and they suggested that the weight of the arms was not great enough to affect total body COM motion. Collectively, these studies do not provide firm experimental evidence about the effects of arm swing on total body COM vertical motion. Therefore, further investigation is needed.

The purpose of this study was to determine the effects of constraining arm swing on the vertical displacement of the body's COM during treadmill walking and examine several common gait variables that may account for or mask differences in the body's COM motion with and without arm swing. It was hypothesized that the vertical displacement of the body's COM would increase when walking with the arms constrained because of the absence of the out-of-phase motion of the arm COM in relation to the COM of the body minus arms. An additional hypothesis was that other gait variables that contribute to COM motion would be sensitive to changes in arm swing so that they could be identified as contributing factors.

2. Methods

2.1. Subjects

Twenty asymptomatic subjects (10 male, 10 female; mean ± SD age: 27.8 ± 6.8 years, height: 1.73 ± 0.11 m, mass: 72.3 ± 16.6 kg) without lower extremity conditions that might have influenced their ability to walk on a treadmill were recruited. Prior to participation, all subjects signed an informed consent form approved by the Institutional Review Board at the affiliated university.

2.2. Protocol

Subjects wore standard laboratory shoes and walked on an instrumented treadmill (100 Hz, Gaitway, Kistler, Inc.) at 1.34 m/s with and without their hands clasped in front of their bodies in a relaxed position while left side sagittal plane lower extremity kinematics were obtained using a Vicon Motus motion capture system (v. 9.2; Denver, CO) sampled at 100 Hz. Subjects walked in each condition for 1.5 min, including one minute for adaptation and 30 s for data acquisition. Reflective markers were attached to the proximal and distal part of the trunk, thigh, leg, and foot segments.

2.3. Data analysis

Ground reaction force data were filtered using a fourth-order Butterworth low-pass filter with a cut-off frequency of 40 Hz and kinematic data were filtered with a cut-off frequency of 6 Hz. The kinetic and kinematic data were further processed and analyzed using custom algorithms in Matlab (v. 2014a; The MathWorks Inc.). Data were collected from at least 12 strides for the kinetics and from at least 7 strides for the kinematics, and then averaged across strides and subjects.

Relative position of the body's COM was calculated from vertical ground reaction force (VGRF) time histories during consecutive strides. Center of mass acceleration was calculated from the summed bilateral VGRFs and then integrated twice to yield relative COM position [12]. The summed bilateral VGRF was calculated as the summation of left and right VGRFs, and it represents the continuous overall VGRF acting on a person. The vertical displacement of the COM was calculated as the difference between maximum and minimum values during a left stride (Fig. 1).

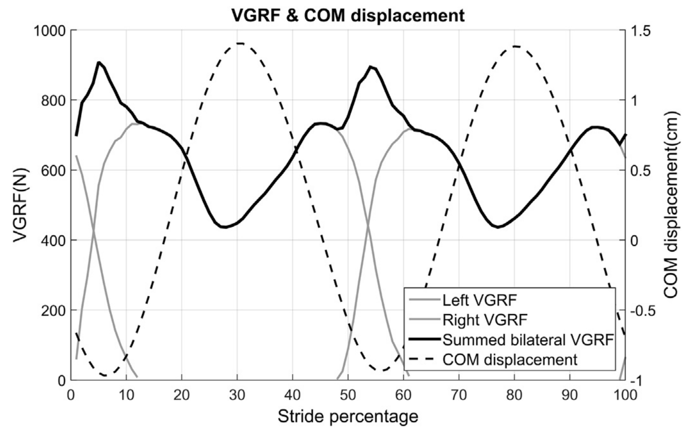

Fig. 1. Example of left, right, and summed bilateral VGRF, and relative COM displacement during walking.

2.4. Statistical analysis

The dependent variables were COM displacement, first and second peak VGRFs (loading and push-off peaks, respectively), and lowest VGRF during the mid-stance (between the first and second peaks) during the left stride, peak summed bilateral VGRF during double limb stance, and bilateral average of stride length and foot contact time. The double integration method provides only relative position of COM data so the examination of the VGRFs was necessary in order to locate where the changes of the COM displacement occurred during gait. An increase or a decrease of VGRF is directly proportional to the relative motion of the body's COM. Statistical analyses (SPSS 21.0) were performed using paired *t*-tests with Bonferroni correction (two-tailed, $\alpha = 0.007$) to determine differences between walking with normal and constrained arm swing. Descriptive examinations of the hip, knee, and ankle joint angles in the sagittal plane were also performed.

3. Results

The vertical COM displacement was significantly greater when subjects walked in the arms constrained condition (arm swing: 4.1 ± 1.2 cm, arm constrained: 4.9 ± 1.2 cm, $p < 0.001$; Fig. 2, Table 1). The vertical COM displacement ranged between 2.4 and 7.1 cm during normal walking and 3.0 and 8.4 cm with the arms

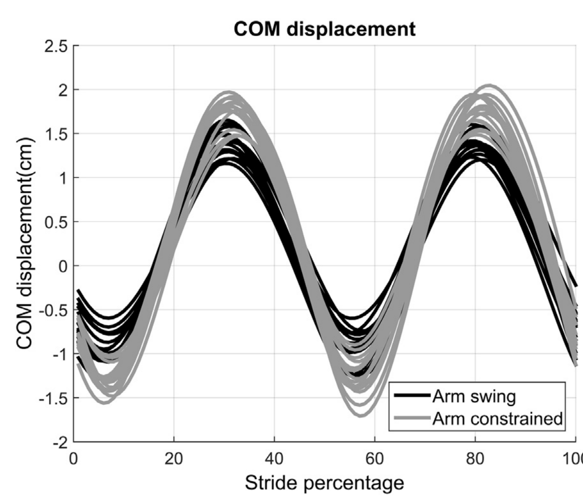

Fig. 2. Example of COM displacement. COM movements during a left stride are shown from an exemplary subject between the arm swing and arm constrained conditions.