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Comprehensive quantitative investigation of arm swing during walking at various speed and surface slope conditions

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ABSTRACT

Previous studies have shown that inclusion of arm swing in gait rehabilitation leads to more effective walking recovery in patients with walking impairments. However, little is known about the correct arm-swing trajectories to be used in gait rehabilitation given the fact that changes in walking conditions affect arm-swing patterns. In this paper we present a comprehensive look at the effects of a variety of conditions on arm-swing patterns during walking. The results describe the effects of surface slope, walking speed, and physical characteristics on arm-swing patterns in healthy individuals. We propose data-driven mathematical models to describe arm-swing trajectories. Thirty individuals (fifteen females and fifteen males) with a wide range of height (1.58–1.91 m) and body mass (49–98 kg), participated in our study. Based on their self-selected walking speed, each participant performed walking trials with four speeds on five surface slopes while their whole-body kinematics were recorded. Statistical analysis showed that walking speed, surface slope, and height were the major factors influencing arm swing during locomotion. The results demonstrate that data-driven models can successfully describe arm-swing trajectories for normal gait under varying walking conditions. The findings also provide insight into the behavior of the elbow during walking.

1. Introduction

Arm swing, which is characterized primarily by arm flexion/extension in the sagittal plane, contributes to balance (Behrman et al., 2000; Brujin, Meijer, Beek, & van Dieen, 2010), regulates rotational body motion Elftman, 1939, and increases metabolic efficiency Collins, Adamczyk, and Kuo, 2009 during locomotion of humans. Most clinical and modeling studies on gait tend to ignore arm swing altogether Pieter, Brujin, and Duysens, 2013. Gait rehabilitation is often focused on the legs and neglect the role of the upper limbs. However, studies show that there are neural couplings between the upper and lower limbs (Behrman et al., 2000) that can be exploited and may improve gait training (Ferris, Huang, & Kao, 2006; Marigold & Misiaszek, 2009; de Kamd, Duysens, & Dietz, 2013). New findings also capitalize on the significant role of exaggerated arm swing in improving dynamic stability during walking, which can be utilized for gait training of patients with walking impairments (Wu et al., 2016; Punt, Bruijn, Wittink, & van Dieën, 2015; Nakakubo et al., 2014). The effect of arm-swing integration in gait rehabilitation becomes more pronounced when patients practice correct arm-swing patterns (de Kamd et al., 2013). However, such patients may have impaired or abnormal arm-swing patterns (Pieter et al., 2013;

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Stephenson, Lamontagne, & De Serres, 2009; Tester et al., 2011; Ford, Wagenaar, & Newell, 2007; Wagenaar & van Emmerik, 1994; Tester, Barbeau, Howand, Cantrell, & Behrman, 2012; Meyns et al., 2012; Ford, Wagenaar, & Newell, 2007), and may require assistance to attain a more natural arm-swing pattern. Thus, the integration of arm swing in gait rehabilitation may lead to more effective walking recovery for patients with walking impairments (Ferris et al., 2006; de Kamd et al., 2013; Stephenson et al., 2009; Sylos-Labini et al., 2014). Robotic or other devices for gait rehabilitation should take this integration into account in their design (Ferris et al., 2006; de Kamd et al., 2013).

Although the integration of arm swing in gait rehabilitation has been attempted by previous studies (Ferris et al., 2006; Yoon, Novandy, Yoon, & Park, 2010; Barnes, Hejrati, & Abbott, 2015), a fundamental question still needs to be answered: What are the correct and normal arm-swing trajectories that should be utilized for gait rehabilitation and assessment under various conditions? Most studies that propose models for describing arm swing during walking have been motivated to answer the question of whether arm swing is passive or active. Elftman (Elftman, 1939) and others (Collins et al., 2009, Pontzer, Holloway, Raichlen, & Lieberman, 2009, 1990, 2012) have reported shoulder moment peaks using inverse dynamics and motion capture. Since shoulder moments vary significantly in these studies, mechanisms other than the acceleration of the shoulder and gravity likely contribute to arm swing (Pieter et al., 2013). Goudriaan et al. (Goudriaan, Jonkers, van Dieen, & Bruijn, 2014) used a musculoskeletal model in OpenSim and found that muscle activity is needed to obtain correct arm swing amplitude and relative phase. Arms have also been modeled as double pendulums in which the muscle activities have been excluded from the model. Jackson, Joseph, and Wyard (1978) utilized the double pendulum model for the first time to explain arm swing, however, their model lacked proper estimation of several key parameters. The interlimb coordination and transition from 2:1 to 1:1 in arm-to-leg swing frequency ratio were investigated, where a driven pendulum model was used to explain arm movements (Kubo, Wagenaar, Saltzman, & Holt, 2004; Webb, Tuttle, & Baksh, 1994; Wagenaar & van Emmerik, 2000; Carpinella, Paolo, & Rabuffetti, 2010). Also, a multibody model was developed for simulation of human locomotion by capitalizing on the relationship between arm swing and foot reaction moments (Park, 2008). Although arm swing can be partially explained by passive dynamics, the finding of EMG activities in arm muscles suggests that passive models alone cannot adequately represent arm swing during normal walking (Kuhtz-Buschbeck & Jing, 2012; Barthelemy & Nielsen, 2010). Since further investigation is still required to determine the extent to which arm swing is passive, most current models may not rely on valid assumptions for describing arm swing during locomotion.

As mentioned earlier, current models try to provide an insight into the mechanism of arm swing, but they may not be appropriate to generate normal arm-swing trajectories for integrating arm swing into gait rehabilitation. Most models have been derived using small samples of human subjects performing a limited number of experimental conditions, and they require the measurement of the arms' and joints' mechanical properties, which are not straightforward to obtain. In addition, gait rehabilitation that includes walking on different surface slopes has been recommended as a preferred training strategy for improving balance and walking ability to prepare patients for functioning in the community (Park & Hwangbo, 2015; Desrosiers, Nadeau, & Duclos, 2015). Arm swing should be considered in slope-walking gait rehabilitation due to its important role in balance and walking ability. Although the effect of surface slope on lower-limb movements has been reported in many studies (Kawamura, Tokuhiro, & Takechi, 1991; Prentice, Hasler, Groves, & Frank, 2004; Dixon & Pearsall, 2010; Tulchin, Orendurff, & Karol, 2010; Major, Twiste, Kenney, & Howard, 2014), to the best of our knowledge, the effect of surface slope on arm swing has not been investigated. Therefore, previous models may not capture the variations in arm swing caused by walking in various conditions (i.e., walking at different speeds on different surface slopes).

The purpose of this study is to provide tools for enabling the integration of arm swing in gait rehabilitation by quantifying normal arm-swing trajectories. This study quantitatively investigates the effect of variations in both walking condition and an individual's physical characteristics on arm-swing patterns during walking. We propose data-driven mathematical models to describe arm-swing trajectory parameters given the mentioned variations. To the best of our knowledge, this is the first time that the effect of surface slope, along with walking speed, on arm swing is reported. We account for the variations between individuals by studying individuals with a wide range of height and body mass who represent a relatively large sample of healthy people with an equal number of male and female participants. Furthermore, this is the first time that the elbow joint angle during various walking conditions is investigated. These findings may help to provide a deeper insight into the mechanism that controls the forearm motion during human locomotion.

The data-driven models can be used to generate arm-swing trajectories in rehabilitative devices aiming to integrate arm swing in gait rehabilitation of patients with walking disabilities (Stephenson et al., 2009; Yoon et al., 2010; Barnes et al., 2015). Furthermore, the elbow joint range of motion and its relative phase with respect to the ipsilateral shoulder joint angle during walking may be useful in the design and control of powered-elbow prostheses (Fougner, Stavdahl, Kyberd, Losier, & Parker, 2012; Bennett, Mitchell, & Goldfarb, 2015).

2. Methods

2.1. Subjects

Thirty healthy subjects participated from a large sample of young individuals with healthy gait. This study was approved by the Institutional Review Board of the University of Utah. We used fifteen male and fifteen female subjects to account for the effect of gender on arm-swing patterns. The age range of our male subjects was 20–35 years (26.00 ± 4.85 years)