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A gait retraining system using augmented-reality to modify footprint parameters: Effects on lower-limb sagittal-plane kinematics

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ABSTRACT

Improving lower-limb flexion/extension angles during walking is important for the treatment of numerous pathologies. Currently, these gait retraining procedures are mostly qualitative, often based on visual assessment and oral instructions. This study aimed to propose an alternative method combining motion capture and display of target footprints on the floor. The second objectives were to determine the error in footprint modifications and the effects of footprint modifications on lower-limb flexion/extension angles. An augmented-reality system made of an optoelectronic motion capture device and video projectors displaying target footprints on the floor was designed. 10 young healthy subjects performed a series of 27 trials, consisting of increased and decreased amplitudes in stride length, step width and foot progression angle. 11 standard features were used to describe and compare lower-limb flexion/extension angles among footprint modifications. Subjects became accustomed to walk on target footprints in less than 10 min, with mean (± SD) precision of 0.020 ± 0.002 m in stride length, 0.022 ± 0.006 m in step width, and 2.7 ± 0.6° in progression angle. Modifying stride length had significant effects on 3/3 hip, 2/4 knee and 4/4 ankle features. Similarly, step width and progression angle modifications affected 2/3 and 1/3 hip, 2/4 and 1/4 knee as well as 3/4 and 2/4 ankle features, respectively. In conclusion, this study introduced an augmented-reality method allowing healthy subjects to modify their footprint parameters rapidly and precisely. Walking with modified footprints changed lower-limb sagittal-plane kinematics. Further research is needed to design rehabilitation protocols for specific pathologies.

1. Introduction

Gait retraining, specifically improving sagittal-plane lower-limb kinematics, is a frequent objective of rehabilitation. This intervention is particularly sought after orthopedic surgery, including reconstruction of the anterior cruciate ligament (Ferber et al., 2004; Scanlan et al., 2013), knee arthroplasty (Hatfield et al., 2011; McClelland et al., 2011) and amputation (Sjödahl et al., 2002). Modifications of ambulatory sagittal-plane kinematics are also considered in the treatment of osteoarthritis (Favre et al., 2016a) and prevention of falls in the elderly (Kerrigan et al., 2001; Watt et al., 2011). The therapy for various neurological disorders, including cerebral palsy (Becher, 2002; Scholtes et al., 2007) and stroke (Mulroy et al., 2003; Sullivan et al., 2008), often aims to act on sagittal-plane kinematics as well. Although improving gait is important for such a range of medical conditions, there is a paucity of quantitative methods to help the patients in these rehabilitation procedures.

Recently, it was shown that the knee adduction moment, a key variable in knee osteoarthritis, could be modified through instructions to walk with different foot progression angle and step width (Simic et al., 2011; Favre et al., 2016b). This suggests that there could be a possibility to help patients modify their lower-limb sagittal-plane kinematics through instructions to change footprint parameters. Literature is however scarce regarding the effects of modifications in foot progression angle, step width and stride length on lower-limb kinematics. A few studies reported knee flexion/extension angles for individuals walking with normal and modified foot progression angles (Lin et al., 2001; Schache et al., 2008; Fregly et al., 2008; Koblauch et al., 2013). Nevertheless, they were conducted for different purposes and provide limited information on the effects of foot progression modifications. Data are even scarcer regarding modifications in step width (Fregly et al.,

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2008), and, to the authors' knowledge, there is no published data about the effects of stride length modifications. However, modifying stride length was reported to affect lower-limb sagittal-plane kinematics during running (Heiderscheit et al., 2011; Napier et al., 2015). Altogether these prior works support the idea that walking with modified footprint parameters is feasible and could be associated with changes in sagittal-plane kinematics. Additional studies are nonetheless required to characterize the effects of such modifications. The sagittal-plane function of the knee has been reported to change with footprint modifications in the frontal and transverse planes (van den Noort et al., 2013; Favre et al., 2016b). Therefore, it is important characterizing the effects due to modifications in the three footprint parameters, not only in stride length.

Systems using haptic or visual feedback have been successfully used to modify foot progression angle and step width (Shull et al., 2011; Hunt et al., 2014; Chen et al., 2017). While they enhance the traditional clinician-based retraining procedures by providing quantitative data, they cannot demonstrate the modifications (i.e., the patients have to adapt based on feedback signals). Furthermore, these systems could become difficult to use when multiple parameters need to be modified, as one feedback signal is required per parameter (Chen et al., 2017). Lately, an alternative approach was introduced where a video projector is used to display footprints on a treadmill and patients are asked to walk while stepping on them (Heeren et al., 2013). This augmented-reality approach is promising as gait modifications can be demonstrated to the patients. Moreover, stride length, step width and foot progression angle can be modified simultaneously using a single easy-to-understand signal: target footprints. Rehabilitation using augmented-reality has shown better results than repetitive movement practiced alone, particularly because it allows more challenging and goal-directed exercises, individual increase in difficulty and higher patient motivation (Sveistrup 2004; Mirelman et al., 2011; Chi-Ho et al., 2014). Consequently, there is an interest in extending the system in (Heeren et al., 2013), notably by adding kinematic measurement and allowing over-ground walking. In addition, it is necessary to evaluate the error in footprint modifications since this information will be decisive to determine rehabilitation strategies.

The first objective of this study was to design an augmented-reality method to display target footprints on the floor, while measuring footprint parameters and lower-limb sagittal-plane angles of the individual undergoing gait retraining. This study then aimed at assessing the error in footprint modifications and determining the effects of footprint modifications on lower-limb flexion/extension angles.

2. Material and methods

2.1. Augmented-reality gait retraining system

The system consisted of a 10 m long walkway instrumented with an optoelectronic motion capture device (Vicon, Oxford, UK), streaming marker positions to a central processing unit at

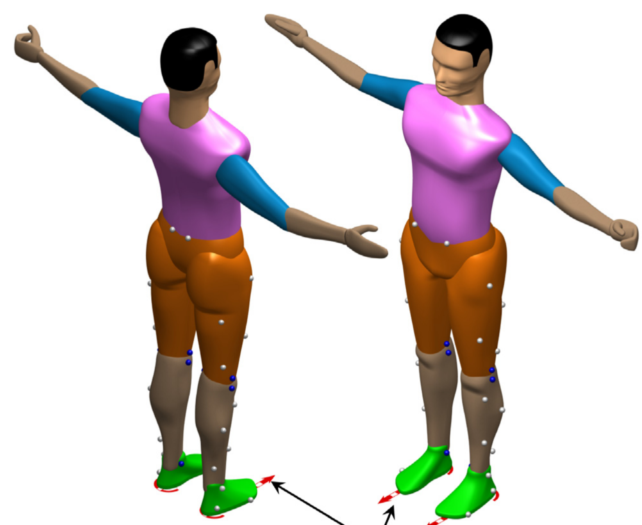

Fig. 2. Illustration of the calibration pose.

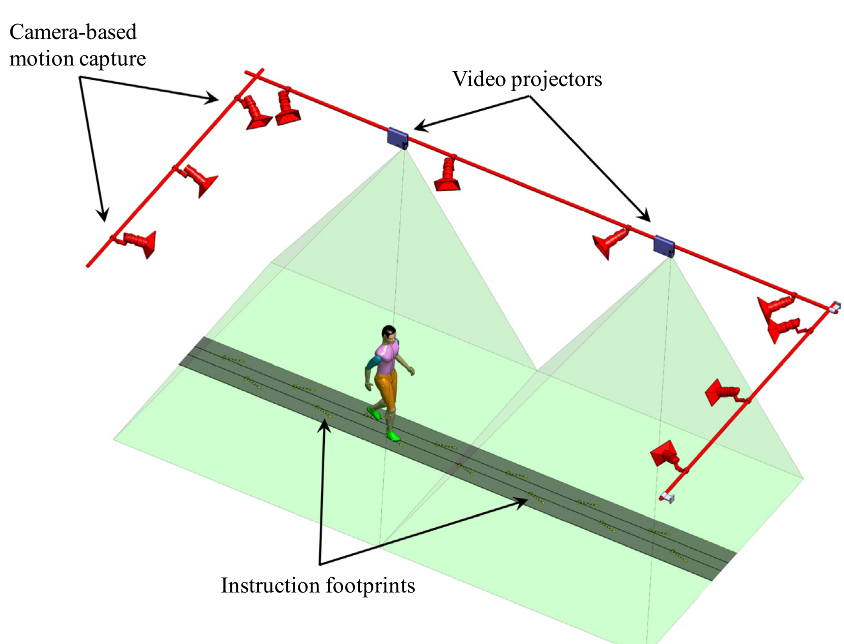

Fig. 1. Illustration of the augmented-reality gait retraining system.