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Abstract Joint impedance plays an important role in postural control and movement. However, current experimental knowledge on lower limb impedance during gait is limited to the ankle joint. We designed the LOwer limb PERturbator (LOPER) aimed to assess knee and hip joint impedance during gait. The LOPER applies force perturbations with a 39 Hz bandwidth, tested on a free-hanging leg. In minimal impedance mode, peak interaction forces during walking are low (<5 N). Also, this mode has a negligible effect on the gait pattern, as it is smaller than the within-subject variability during normal walking. In short, the LOPER is a transparent device able to elicit a clear response at both hip and knee joints to investigate lower limb dynamics. A second motor added to the LOPER could improve isolation of the perturbation contribution to knee and hip dynamics. People with neurological disorders can benefit from knowledge of joint impedance during gait through improved biomimetic devices and clinical decision making.

1 Introduction

Joint impedance, especially its stiffness component, plays an important role in postural control and movement. For example, humans adapt ankle, knee and hip joint impedance during walking to enable a successful gait pattern and interaction with their environment. Joint impedance determines the mechanical resistance to external

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perturbations and can be estimated by measuring the joint's response to perturbations. Several neurological disorders, e.g. spinal cord injury, affect joint impedance and people's ability to modulate it [1]. Knowledge of lower limb joint impedance during gait could be used to support people with these neurological disorders through the development of better biomimetic devices and improved clinical decision making [2, 3]. However, current experimental knowledge on lower limb impedance during walking is limited to the ankle joint [2, 4].

Experimental joint impedance estimation during gait requires a device able to apply perturbations without affecting gait when no perturbations are applied, i.e. a transparent device. Multiple devices have been developed to determine knee or ankle impedance during walking, e.g. [5, 6]. Unfortunately, to our knowledge, no device currently complies with the following requirements: (1) assess knee and hip joint impedance during gait; and (2) have a negligible effect on the unperturbed gait pattern. This study presents the LOwer limb PERturbator (LOPER), aimed to comply with these two requirements, and evaluates its transparency during gait.

2 Material and Methods

The LOPER consists of a motor, two carbon fiber rods, a load cell, an aluminium frame and a brace, which is connected to the left upper leg via Velcro straps, see Fig. 1. To minimize the additional load on the user, the motor (SMH60, Parker, USA) is bolted on a grounded, steel structure. The angular motor motion is translated into a linear motion via the two carbon fiber rods and a ball joint linkage. To minimize interaction forces, first the load cell (FUTEK FSH00086, USA) measuring interaction force at 1000 Hz is implemented close to the human limb. Second, the LOPER is controlled using an admittance control law with low virtual impedance. To prevent human-robot interaction instability due to this low virtual impedance, indirect PI force control with inner-loop velocity control was implemented [7].

Five people (1 female, 26.4 ± 1.3 yr, height 1.71 ± 0.09 m, weight 68.4 ± 11.5 kg) participated in the evaluation study. The University of Twente EWI/ET ethics committee approved the study and all participants provided written informed consent. First, the force bandwidth was tested on a single participant in a standing posture on a free-hanging left leg. Second, participants walked 3×4 min. on a split-belt treadmill (custom Y-Mill, Forcelink, The Netherlands) to assess the minimal impedance mode and ability to apply perturbations. In order, participants walked: (1) without the LOPER; (2) with the LOPER in minimal impedance mode (unperturbed); (3) with pulse-shaped force perturbations (width 100 ms, amplitude 40 N) applied 50 ms after toe-off. These perturbations were applied randomly after every 3–5 strides during the swing phase of the left leg. A motion capture system (Qualysis AB, Sweden) recorded marker positions on anatomical landmarks at 128 Hz and these were used

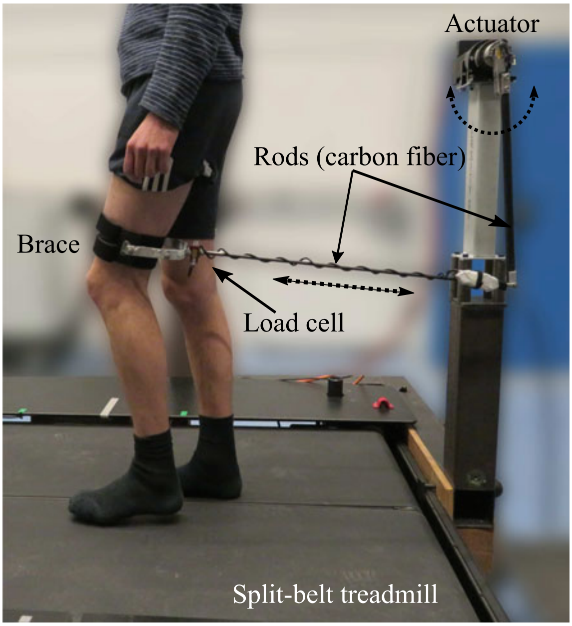

Fig. 1 Overview of the LOPER (LOwer limb PERturbator). The rotary actuator is placed on a steel support frame. The rotational actuator motion is converted to a linear motion through the carbon-fiber rods with a ball joint linkage. The motion is transferred into the human leg through an aluminum frame with brace connected to the user. The load cell measuring interaction forces is placed between the aluminum frame and carbon-fiber rod

to compute knee and hip joint angles (OpenSim4.0, gait 2392 model). Ensemble averages over strides were used to compute outcome measures: root mean square (RMS) of interaction force, maximal absolute interaction force, RMS error (RMSE) between joint angles of trials with and without device and intra subject variability (ISV_{ave}) [8].

3 Results

We designed and evaluated the LOPER, which can apply force perturbations to the left upper leg, see Fig. 2. First, a 39 Hz force bandwidth was found when tested on a free-hanging leg. This bandwidth is higher than the 10 Hz bandwidth required based on knee and hip joint dynamics during postural tasks [9]. Second, maximum absolute interaction force across-subjects (4.63 ± 0.79 N) and RMS interaction forces (2.00 ± 0.20 N) were lower than, respectively, 20 and 10 N required to obtain negligible effects on a gait pattern [8]. Third, the average RMSEs for hip and knee angle between the trial without the device and the minimal impedance trial were 0.030 ± 0.010 rad and 0.052 ± 0.026 rad respectively. Both RMSEs were lower than the ISV_{ave} (0.047 and 0.086 rad) for walking without the device, again confirming the negligible effect that the device, in minimal impedance mode, had on the gait pattern.

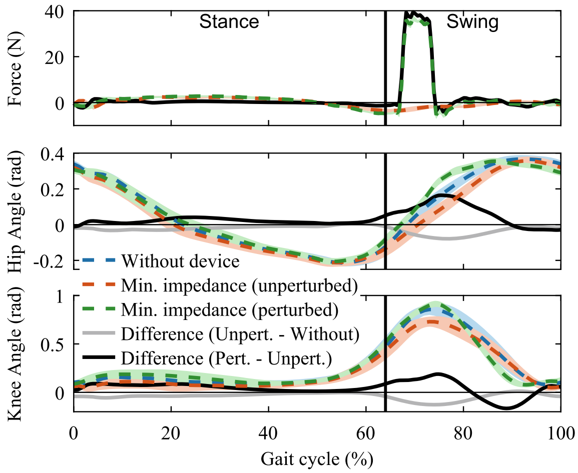

Fig. 2 Interaction forces (top) and hip (middle) and knee (bottom) joint angles for left leg of representative participant during walking. The lines show averages across strides without device, unperturbed strides with device and perturbed strides with device, as well as the differences between these conditions. The shaded areas show the standard deviation across strides. The positive axes show force in forward direction and a flexion angle. Start (0%) of gait cycle is at left heel strike

4 Discussion and Conclusions

This study presents the LOwer limb PERturbator (LOPER), aimed to experimentally assess knee and hip joint impedance during gait. The LOPER applies force perturbations with a 39 Hz bandwidth, when tested on a free-hanging leg. In minimal impedance mode, peak interaction forces during walking are low (<5 N) and the effect on the gait pattern is smaller than within-subject variability during normal walking. The largest differences between the trials with and without the device were found during the beginning/mid swing, likely due to the larger interaction forces observed, see Fig. 2. These larger interaction forces can be attributed to the virtual mass and high accelerations at this portion of the gait cycle.

Moreover, perturbations affect both knee and hip joint simultaneously, see Fig. 2, which makes it difficult to analyze the dynamics of a single joint. This simultaneous excitation is due to the placement of the motor on a grounded structure to minimize the additional load on the user. As result, the angular motor motion is translated into a linear motion and the motor thus applies a force, not a torque, to the lower limb. Future work may therefore include the use of a biomechanical model to analyze the experimental data or the use of a second motor to apply perturbations to both lower and upper leg simultaneously. Furthermore, we chose to only apply perturbations during the swing phase. Ultimately, we will use the device to investigate knee and hip joint impedance during the entire gait cycle. In short, the LOPER is a transparent device able to elicit a clear response at both hip and knee joints to investigate lower limb dynamics.

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