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Feasibility and reliability of using an exoskeleton to emulate muscle contractures during walking

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ABSTRACT

Contracture is a permanent shortening of the muscle–tendon–ligament complex that limits joint mobility. Contracture is involved in many diseases (cerebral palsy, stroke, etc.) and can impair walking and other activities of daily living. The purpose of this study was to quantify the reliability of an exoskeleton designed to emulate lower limb muscle contractures unilaterally and bilaterally during walking.

An exoskeleton was built according to the following design criteria: adjustable to different morphologies; respect of the principal lines of muscular actions; placement of reflective markers on anatomical landmarks; and the ability to replicate the contractures of eight muscles of the lower limb unilaterally and bilaterally (psoas, rectus femoris, hamstring, hip adductors, gastrocnemius, soleus, tibialis posterior, and peroneus). Sixteen combinations of contractures were emulated on the unilateral and bilateral muscles of nine healthy participants. Two sessions of gait analysis were performed at weekly intervals to assess the reliability of the emulated contractures. Discrete variables were extracted from the kinematics to analyse the reliability.

The exoskeleton did not affect normal walking when contractures were not emulated. Kinematic reliability varied from poor to excellent depending on the targeted muscle. Reliability was good for the bilateral and unilateral gastrocnemius, soleus, and tibialis posterior as well as the bilateral hamstring and unilateral hip adductors. The exoskeleton can be used to replicate contracture on healthy participants. The exoskeleton will allow us to differentiate primary and compensatory effects of muscle contractures on gait kinematics.

1. Introduction

To be able to walk without feeling pain, fatigue, or another alteration is considered a priority in daily life and is linked to the quality of life [1,2]. Numerous impairments in the neurological and/or musculoskeletal systems generate walking alterations. A precise understanding of these alterations is required to optimise therapeutic strategies. Among impairments, contractures in the lower limbs occur frequently and alter human walking [1,2]. Contracture induces a restricted passive range of motion (ROM) [2,3] as a result of limited extensibility or increased stiffness of the soft tissues around the joints such as ligaments, capsule, tendons and muscles [2]. Contractures have been reported in numerous pathologies such as cerebral palsy [4], multiple sclerosis, spinal cord injury and stroke [1]. Different mechanisms can be implicated in contractures, such as muscular shortening, shortening of ligaments, joint capsule alterations, intra-articular adhesions and proliferation of fibro-fatty tissues into the joint [5]. The main causes of contractures are immobilisation [6], muscle weakness [7] and spasticity [8]. The consequences of contractures on activities of daily life include walking deviations [9], loss of balance with risk of fall [1] and bone deformities affecting posture [10].

Experimental approaches have been used to induce the ROM limitations of joints using mechanical methods (rope, elastic, orthotics, and so on). Matjacic and Olensek [11] investigated

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biomechanical characterisation and the clinical implication of artificially induced crouch walking, and this approach allowed them to determine the extent to which the iliopsoas and hamstring are implicated in crouch walking. Goodman et al. [12] and Houx et al. [13] evaluated the compensation mechanisms of toe-walking unilaterally. They explained that in patients with hemiplegia, hip ROM limitations and knee extension in gait were not caused by hamstring and/or hip flexor contractures but were linked to ankle plantarflexor contractures only. Harato et al. [14] studied the influence of knee contractures on trunk kinematics and determined the minimum degree of contracture required to obtain a significant difference in trunk movements in gait. Whitehead et al. [15] emulated hamstring contracture with an exoskeleton at the hip and knee level. They determined that to have an effect on knee kinematics, the popliteal angle would need to exceed 85°. These different results provide an important understanding on pathologic gait and support the links between clinical examination and gait deviations. However, these studies were focused on one or two muscles. To our knowledge, no study has used an external system that is able to emulate a combination of contractures on the main muscular groups of the lower limb. Therefore, the purpose of this study was to quantify the reliability of an exoskeleton designed to emulate lower limb muscle contractures unilaterally and bilaterally during walking.

2. Method

2.1. Design exoskeleton:

An exoskeleton was built based on the method of Matjacic and Olensek [11] with the addition of certain criteria with:

Design criteria:

- Respects the main lines of action of the muscles.
- Is adjustable according to the anthropometry of participants.
- Avoids relative displacement between the plastic cuffs and the supporting body segment.
- Has the possibility to perform motion capture with reflective markers placed directly on the skin.

Assessed criteria:

- No modification of gait with the exoskeleton if no contractures were emulated.
- Can replicate contractures of the main lower limb muscles affected by contractures with a good level of reliability.

The exoskeleton was designed and built in collaboration with the Giglio Partners Orthopedie group based in Geneva, Switzerland. The exoskeleton, named “MIkE” for **M**uscle contracture **I**nduced by an **E**xos**k**eleton, is presented in Fig. 1. It was built to bilaterally embrace the pelvis, the thigh and the shank with plastic cuffs and with modified shoes that included attachment points. A particular cut was made on the plastic cuffs to enable reflective markers to be placed directly on the skin as requested for clinical gait analysis (CGA). Moreover, this design enabled each participant to walk with and without the exoskeleton without removing any reflective marker.

The exoskeleton was built to induce unilateral and bilateral contractures in relation to the following main muscles or muscle groups affected by contractures in the lower body and identified in the literature: hamstring, iliopsoas, hip adductor, rectus femoris, gastrocnemius, soleus, tibialis posterior and peroneus [16–19]. Contractures were induced by ropes attached to rings. The characteristics of the ropes were chosen to avoid a sudden stop and to mimic a progressive increase of stiffness at the limit of the ROM as reported for muscle contractures [2]. Because muscle insertion points are usually deep and multiple, only the main muscle lines of action were used to define the ropes attached to the rings. To respect the anthropometry of the participants, two different sizes of exoskeleton were built.

2.2. Protocol:

2.2.1. Participants:

Nine healthy participants (6 females, 3 males) ages 18 to 35 years old (age: 27 ± 5.7 years; height: 1.70 m ± 0.09; weight 66.3 kg ± 7.8), with no known neurologic or orthopaedic problems, participated in this study. Ethical approval and participant consent were obtained before the data collection began.

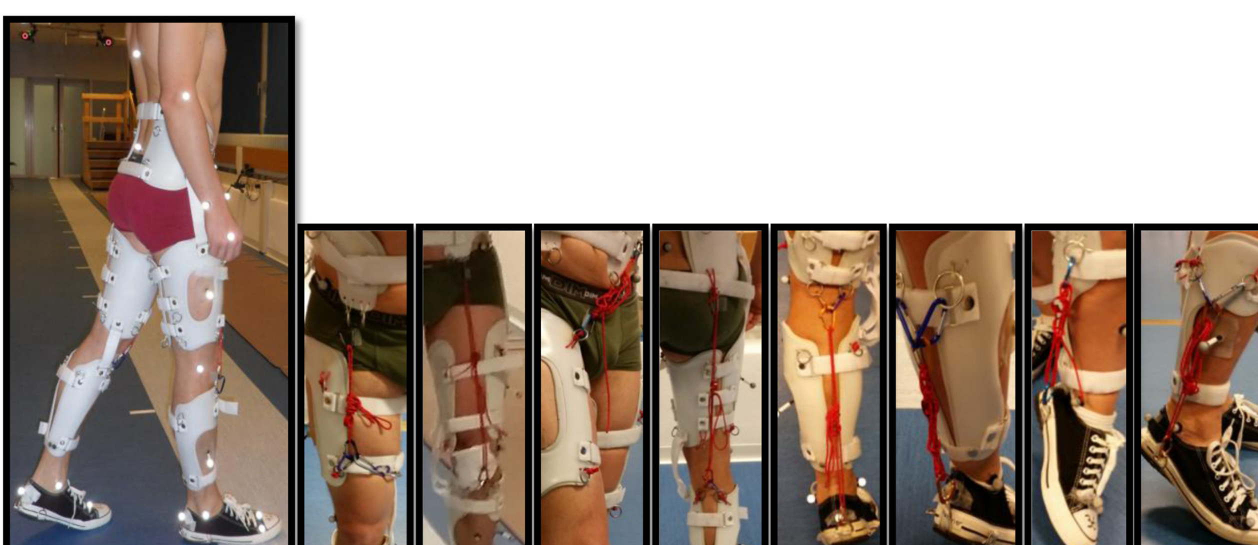

Fig. 1. Pictures of the exoskeleton « MIkE » (**M**uscle contracture **I**nduced by an **E**xos**k**eleton). From left to right: complete exoskeleton without contracture; psoas contracture; rectus femoris contracture; adductor contracture; hamstring contracture; gastrocnemius contracture; soleus contracture; tibialis posterior contracture; peroneus contracture.