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Compensations in lower limb joint work during walking in response to unilateral calf muscle weakness

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ABSTRACT

Background: Patients with calf muscle weakness due to neuromuscular disorders have a reduced ankle push-off work, which leads to increased energy dissipation at contralateral heel-strike. Consequently, compensatory positive work needs to be generated, which is mechanically less efficient. It is unknown whether neuromuscular disorder patients compensate with their ipsilateral hip and/or contralateral leg; and if such compensatory joint work is related to walking energy cost.

Research question: Do patients with calf muscle weakness compensate for the increase in negative joint work by increasing positive ipsilateral hip work and/or positive contralateral leg work? And is the total mechanical work related with walking energy cost?

Methods: Seventeen patients with unilateral flaccid calf muscle weakness and 10 healthy individuals performed the following two tests: i) a barefoot 3D gait analysis at comfortable speed and matched control speed (i.e. 0.4 non-dimensional) to assess lower limb joint work and ii) a 6-minute walk test at comfortable speed to assess walking energy cost.

Results: Patients had a lower comfortable walking speed compared to healthy individuals (1.05 vs 1.36 m/s, $p < 0.001$) and did not increase positive lower limb joint work at comfortable speed. At matched speed (1.25 m/s), patients showed increased positive work at their ipsilateral hip (0.38 ± 0.08 vs 0.27 ± 0.07, $p = 0.001$) and/or contralateral leg (0.99 ± 0.14 vs 0.69 ± 0.14, $p < 0.001$). Patients with weakest plantar flexors used both strategies. No relation between total positive work and walking energy cost was found ($r = 0.43$, $p = 0.122$).

Significance: Patients with unilateral calf muscle weakness compensated for reduced ankle push-off work by lowering their comfortable walking speed or, at matched speed, by generating additional positive joint work at the ipsilateral hip and/or contralateral leg. The additional positive joint work at matched speed did not explain the elevated walking energy cost at comfortable speed, which needs further exploration.

1. Introduction

During walking, the calf muscles provide most of the propulsive power [1,2]. In patients with neuromuscular disorders, calf muscles are often weakened, which reduces propulsive (push-off) power [3]. This induces the need for compensatory positive power elsewhere, which is mechanically less efficient [4,5]. An increased metabolic cost of walking is also observed in patients with calf muscle weakness [6,7].

During normal gait, the calf muscles are the primary generator of positive power [1,8] as 35–45% of the total power is generated at the ankle joint [9]. This power is used for forward propulsion during pre-swing, and to accelerate the body center of mass upward just prior to and at the moment of contralateral heel-strike [10]. When the calf muscles are weakened and ankle power is decreased, the upward acceleration of the body center of mass pre-emptive to contralateral foot collision will be lower and, consequently, the leading foot hits the ground at a higher velocity [4,5]. This higher velocity results in more energy dissipation (i.e. negative work) at contralateral heel-strike [4,5,11]. To overcome such increment in negative joint work at contralateral heel-strike and the decrease in push-off work, patients need to compensate as total positive work must offset total negative work over a full gait cycle at steady state walking [4,11].

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Multiple strategies to compensate for a reduced ankle push-off power may be used. Based on model simulations, compensating by increasing ipsilateral (i.e. affected leg) hip work during stance and swing results in normal gait kinematics when calf muscle strength is moderately reduced (e.g. up to 30%) [2,12]. Experimentally, it has been shown that hemiplegic cerebral palsy patients use this strategy [13,14]. Yet, others have indicated that compensating with the ipsilateral hip during stance compromises (energy) efficiency, as generating more positive work in this phase increases the center of mass velocity, which, accordingly, increases the impact and the negative work at contralateral heel strike [15]. Increasing non-affected leg work to compensate is suggested to be a more (energy) efficient strategy [15]. However, this strategy has only been reported in combination with an increase in ipsilateral hip work in severely affected hemiplegic cerebral palsy children [14] and unilateral below-knee amputees [15,16].

While several compensation strategies for impaired push-off work have been described, most studies did not concern patients with neuromuscular disorders with flaccid calf muscle weakness [13–18]. Also, compensations were mostly assessed at comfortable walking speed, which limits the comparison with healthy individuals walking at higher speed. Consequently, which compensatory strategies are used by patients with flaccid calf weakness is still poorly understood, while these compensation may explain the increased energy demands of walking.

The aims of this explorative study in patients with unilateral flaccid calf muscle weakness were to examine 1) if negative joint work at contralateral heel strike is increased compared to healthy individuals and if this relates to the amount of ankle work in pre-swing when walking at comfortable and matched control speed, 2) whether an increase in negative joint work is compensated for by increased positive ipsilateral hip work and/or positive contralateral leg work, and if patients using either strategy differ in (calf) muscle strength, total positive work and walking energy cost, and 3) if total positive joint work is related with walking energy cost.

Based on the inverted double pendulum model, we hypothesize that the amount of negative joint work increases with a more profound push-off deficit and that patients compensate with both the ipsilateral hip and contralateral leg when either compensation alone is insufficient [4,5]. Furthermore, it is hypothesized that the increases in positive joint work may, in part, explain the increment in walking energy cost [19–21].

2. Methods

2.1. Study population

Medical records of patients referred to the gait lab at our University hospital Rehabilitation department and patients who participated in the PROOF-AFO trial [22] were screened for the following inclusion criteria; diagnosed with a neuromuscular disease or nerve damage; presence of calf muscle weakness in one leg (i.e. a manual muscle strength graded according to the Medical Research Council (MRC) scale < 5 [23] and/or being unable to perform > 3 heel rises [24]); able to walk for 6 min with or without assistive devices; and being able to walk barefoot and at matched control speed (i.e. 0.4 non-dimensional) [25]. Ten healthy individuals without known calf muscle weakness served as a control group. The medical ethics committee of our university hospital approved the study.

2.2. Procedures and measurements

After participants provided written informed consent, the following tests were performed: 3D gait analysis to assess lower limb joint work, 6-minute walk test to measure walking energy cost and isometric muscle strength tests.

2.2.1. 3D gait analysis

Ankle, knee, and hip kinematics and kinetics were assessed according to the Plug-in-Gait model with a 3D 8-camera Vicon MX 1.3 system (VICON, Oxford, UK), and two force plates in series (OR6-7, AMTI, Watertown, MA, USA), embedded in the center of a 12 m walkway. Participants were instructed to walk barefoot and without an assistive device along the walkway at two different speeds; (i) at comfortable walking speed (CWS), and (ii) at 0.40 non-dimensional fixed matched walking speed (FWS), which is approximately 1.25 m/s [25]. For both conditions, three trials were acquired in which (i) each foot landed solely and completely on one force plate and (ii) walking speed in the FWS condition was within $\pm$ 0.05 m/s of the FWS, which was checked using infrared sensors (Chronoprinter 520, TAG Heuer, Bolzano, Italy).

2.2.2. 6-min walk test

Walking energy cost at CWS while walking with shoes (and assistive device if necessary) was assessed during a 6-minute walk test at a 35-meter oval track with simultaneous breath-by-breath gas analysis (K4b2, Cosmed, Rome, Italy). All patients walked the track counterclockwise. From the gas analysis, we derived oxygen uptake (VO_2) and carbon dioxide production (VCO_2).

2.2.3. Isometric muscle strength tests

Isometric strength of the plantarflexors and dorsiflexors was measured with a fixed dynamometer (Biodex type 3, Corp., Shirley, NY, USA). The ankle was positioned in 15° plantarflexion, while the shank was positioned horizontally, the knee in approximately 60° and the back of the chair in 70°. The highest recorded value (in Nm) of three maximal voluntary contractions, with 30 s rest between contractions, was used for analysis [26].

MRC scores of the following muscles were extracted from the patients' medical record and summed to calculate an MRC sum score per leg (range: 0–40); hip abduction, hip adduction, hip flexion, hip extension, knee flexion, knee extension and ankle plantar flexion and dorsiflexion. In addition, ankle range of motion was extracted from the medical record.

2.3. Data processing

2.3.1. 3D gait analysis

3D gait data were processed with Vicon Nexus (VICON, Oxford, UK). Based on force plate data and marker trajectories, five gait phases were determined according to Perry et al. [3]; loading response, midstance, terminal stance, pre-swing and swing

We calculated the positive and negative work of the ankle, knee and hip joints (J/kg) for one full gait cycle and for each of the five gait phases by integrating the positive and negative intervals of the joint powers for the respective period using custom scripts in Matlab 2015 (The Mathworks, Natick, MA, USA).

Contralateral positive and negative leg work were calculated by taking the sum of the positive and negative joint work generated at the ankle, knee and hip of the non-affected leg, respectively.

Total positive work was calculated as the sum of the positive joint work of the ankle, knee and hip of both legs. The percentage of total positive work generated at the different joints was also calculated.

2.3.2. 6-min walk test

For analysis, a steady state period for VO_2, VCO_2 and walking speed of at least 60 s within the last three minutes of the test was determined with a custom written Matlab script (version 2015, MathWorks, Natick, MA). Walking energy cost (J/kg/m) was calculated over the steady state period as follows:

$(((4.940^* (VO_2/VCO_2)\ 16.040)^*VO_2)/\ \text{walking speed})$ [27].