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Full length article

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 ± 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].

Table 1
Participant characteristics.

	Sex	Age	BMI	Disease	Affected leg	PF strength Nm[a]	MRC PF[a]	MRC DF[a]	MRC KE[a]	MRC KF[a]	Sensory deficits	Ankle joint range of motion DF/PF	Compensation strategy
P1	M	68	26.3	Polio	Right	29	4−	0	5−	5	No	NA	Ipsilateral hip
P2	M	65	30.4	Spinal Stenosis	Right	21	5−	0	5	5	Mild	0–0–40	Ipsilateral hip
P3	F	60	24.8	LRS L5-S1	Right	18	4	4	4	5	Mild	5–0–40	Ipsilateral hip
P4	M	61	25.5	Polio	Right	14	3	1	5	5	No	0–10–45	Contralateral leg
P5	M	67	25.5	Polio	Right	57	4+	4	4+	4−	No	0–0–30	Contralateral leg
P6	M	70	26.0	Polio	Right	18	4+	3	4+	4+	No	0–10–60	Contralateral leg
P7	M	58	17.7	Polio	Right	NA	0	4	5−	5	No	40–10–0	Contralateral leg
P8	M	31	21.7	Polio	Left	0	2	4	5	5	No	25–0–20	Contralateral leg
P9	F	72	27.7	Polio	Left	0	3	2	5	4	No	0–0–15	Contralateral leg
P10	F	21	17.8	Cauda equina	Left	18	4	5	5	5	Mild	20–0–45	Contralateral leg
P11	M	56	24.8	LRS L5-S1	Left	20	4	5	5	5	No	12–0–40	Contralateral leg
P12	F	58	23.5	Polio	Right	0	3	2	5	5	No	0–5–30	Ipsilateral hip + contralateral leg
P13	M	68	26.6	Polio	Right	0	2	1	5	5	No	0–5–20	Ipsilateral hip + contralateral leg
P14	F	47	28.5	Polio	Right	0	3	5	5	4+	No	NA	Ipsilateral hip + contralateral leg
P15	F	51	21.4	Polio	Left	7	2	4+	5−	5−	No	20–0–30	Ipsilateral hip + contralateral leg
P16	F	61	31.6	Polio	Left	35	4	1	4	4	No	5–0–50	Ipsilateral hip + contralateral leg
Mean/median	9M/7F	57.1 ± 14.0	24.6 ± 3.2	–	–	15.8 ± 16.1	3.0 [b] [2–4]	4.0 [b] [4–1]	5.0 [b] [4+ −5]	5.0 [b] [4.5 − 5]	–	–	–

Abbreviations: BMI = body mass index, MRC = Medical research council scale, PF = plantar flexion, DF = dorsiflexion, KE = knee extension, KF = knee flexion, M = male, F = female, LRS = Lumbar radicular syndrome, NA = not available.

[a] Strength of the affected leg.

[b] Presentedas median [interquartile range].

2.4. Data analysis

Patient characteristics were analyzed with descriptive statistics. To examine if contralateral negative joint work during loading response was increased in patients compared to healthy individuals and whether patients generated more ipsilateral positive hip work and/or contralateral positive leg work when walking at CWS and FWS, we used independent samples *t*-tests.

For determining how patients compensated, subgroups were made based on ipsilateral positive hip work and contralateral positive leg work at FWS. Each parameter was divided into 'normal' or 'increased', where 'increased' was defined as 1.65 standard deviations higher compared to the mean value observed in healthy individuals. We classified three subgroups: positive ipsilateral hip work increased (hip work group); positive contralateral leg work increased (leg work group); and positive ipsilateral hip work and positive contralateral leg work increased (hip + leg work group). Descriptive statistics were used to characterize patients in each group in terms of muscle strength, total positive joint work, and walking energy cost.

Pearson correlations were used to examine if total positive joint work over a full gait cycle and per meter at FWS and walking energy cost at CWS were related. When walking at FWS, the speed dependence of mechanical work is controlled for. We assumed that patients who generate the most positive work at FWS would also compensate the most at CWS, and therefore, positive work at FWS was considered a measure of compensatory work.

Statistical analyses were performed using SPSS Version 23 (SPSS Inc., Chicago, USA), with the level of significance set at $\alpha = 0.05$.

3. Results

3.1. Patient characteristics

Twenty patients signed informed consent, of whom 3 were excluded because they were unable to walk at 0.4 non-dimensional speed and 1 because of an extreme BMI (42.9) which makes the gait analysis less reliable. Characteristics of the remaining 16 patients (9 males) are presented in Table 1. Patients were significantly older compared to healthy individuals (n = 10, 4 males, mean age: 32.5 ± 14.8, $p < 0.001$) and calf muscle strength of their affected leg was significantly less (15.8 ± 16.0 vs 41.5 ± 19.7, $p < 0.001$).

3.2. Contralateral negative joint work

CWS of patients was significantly lower compared to healthy individuals (patients: 1.05 ± 0.17 vs healthy: 1.36 ± 0.10 m/s, $p < 0.001$). At CWS, contralateral negative leg work during loading response in patients was not significantly different from healthy individuals (−0.11 ± 0.08 vs −0.08 ± 0.03 J/kg, $p = 0.083$). At FWS, contralateral negative leg work was increased by 150% in patients (−0.16 ± 0.07 J/kg) compared to healthy individuals (−0.06 ± 0.02 J/kg, $p < 0.001$) and significantly related with ipsilateral positive ankle work in pre-swing (r = 0.62, $p = 0.001$).

3.3. Compensatory positive joint work

While walking at CWS, ipsilateral positive hip work (patients: 0.29 ± 0.06 vs healthy: 0.31 ± 0.09 J/kg, $p = 0.392$) and contralateral positive leg work over the full gait cycle did not differ significantly between patients and healthy individuals (patients: 0.82 ± 0.22 vs healthy: 0.77 ± 0.18 J/kg, $p = 0.589$). The percentage ipsilateral hip work and contralateral leg work was higher in patients compared to healthy individuals (Table 2).

At FWS, ipsilateral positive hip and contralateral positive leg work over the full gait cycle were significantly higher in patients compared to healthy individuals (hip: 0.38 ± 0.08 vs 0.27 ± 0.07 J/kg, $p = 0.001$,

Table 2
Gait and strength characteristics of the compensation subgroups.

	Healthy individuals (n = 10)	Patients (n = 16)	Hip work group (n = 3)	Leg work group (n = 8)	Hip + leg work group (n = 5)
CWS 3D-gait analysis					
Walking speed (m/s)	1.36 ± 0.10	1.05 ± 0.16[a]	0.90 ± 0.18	1.14 ± 0.13	1.00 ± 0.15
Total positive work full gait cycle (J/kg)	1.54 ± 0.36	1.36 ± 0.33	1.09 ± 0.25	1.48 ± 0.36	1.31 ± 0.26
Ipsilateral positive ankle work full gait cycle (J/kg) (% of total)	0.33 ± 0.07 (21.4%)	0.14 ± 0.11[a] (10.3%)	0.16 ± 0.09 (14.7%)	0.13 ± 0.12 (8.8%)	0.14 ± 0.14 (10.7%)
Ipsilateral positive hip work full gait cycle (J/kg) (% of total)	0.31 ± 0.09 (20.1%)	0.29 ± 0.06 (21.3%)	0.31 ± 0.03 (28.4%)	0.28 ± 0.06 (18.9%)	0.30 ± 0.06 (22.9%)
Contralateral positive leg work full gait cycle (J/kg) (% of total)	0.77 ± 0.18 (50.0%)	0.82 ± 0.22 (60.3%)	0.54 ± 0.16 (49.5%)	0.93 ± 0.20 (62.8%)	0.80 ± 0.13 (61.0%)
CWS 6-minute walk test					
Energy cost (J/kg/m)	3.3 ± 0.33	4.29 ± 0.71[a]	4.38 ± 1.05	4.39 ± 0.72	3.94 ± 0.30 (n = 3)
FWS 3D-gait analysis					
Walking speed (m/s)	1.23 ± 0.05	1.25 ± 0.06	1.19 ± 0.01	1.26 ± 0.05	1.26 ± 0.10
Total positive work over full gait cycle (J/kg)	1.38 ± 0.28	1.68 ± 0.18[a]	1.53 ± 0.18	1.69 ± 0.19	1.73 ± 0.15
Ipsilateral positive ankle work full gait cycle (J/kg) (% of total)	0.31 ± 0.063 (22.5%)	0.16 ± 0.12[a] (9.5%)	0.17 ± 0.10 (11.1%)	0.14 ± 0.12 (8.3%)	0.17 ± 0.15 (9.8%)
Ipsilateral positive hip work full gait cycle (J/kg) (% of total)	0.27 ± 0.07 (19.6%)	0.38 ± 0.08[a] (22.6%)	0.44 ± 0.11 (28.7%)	0.33 ± 0.04 (19.5%)	0.44 ± 0.6 (25.4%)
Contralateral positive leg work full gait cycle (J/kg) (% of total)	0.69 ± 0.14 (50%)	0.99 ± 0.14[a] (58.9%)	0.79 ± 0.05 (51.6%)	1.05 ± 0.14 (62.1%)	1.01 ± 0.06 (57.8%)
MRC strength scores affected leg [b]					
MRC plantar flexion	5	3 (0–5)	4 (4–5)	3.5 (0–5)	3 (2–4)
MRC dorsiflexion	5	3.5 (0–5)	1.3 (0–4)	4 (1–5)	2 (1–5)
MRC hip flexion	5	5 (4–5)	5 (4–5)	5 (4.5–5)	5 (4–5)
MRC sum score	40	35 (32.3–39)	34.5 (32.5–36)	35 (32.5–39)	34 (32.3–35)
Biodex strength scores affected leg					
Plantar flexion (Nm)	45.8 ± 16.0	15.8 ± 16.1[a]	22.6 ± 5.7	18.1 ± 19.1	8.4 ± 15.2
Dorsiflexion (Nm)	29.5 ± 6.8	13.1 ± 16.2[a]	10.3 ± 17.9	14.0 ± 12.0	16.6 ± 23.5

Abbreviations: FWS = fixed walking speed CWS = comfortable walking speed.
[a] Significantly different between healthy individuals and all patients.
[b] Presented as median (range).

contralateral leg: 0.99 ± 0.14 vs 0.69 ± 0.14 J/kg, $p < 0.001$) (Figs. 1 and 2). In the ipsilateral hip, more work was generated in loading response and swing, and in the contralateral leg more positive work was generated at the hip and knee joint during loading response, mid-stance and swing phase (Figs. 1 and 3). (Graphs of the joint angles and moments are attached as supplementary material).

3.4. *Compensation strategy subgroups*

Three patients (19%) compensated by increasing ipsilateral positive hip work, eight (50%) by increasing contralateral positive leg work and five (31%) by increasing both. As shown in Table 2, the hip work group generated considerably less total positive work (1.53 J/kg) at FWS compared to the other two subgroups (1.69 and 1.73 J/kg for the leg work group and hip + leg work group, respectively). The hip work group and leg work group had stronger plantar flexors (hip: 22.6 Nm, contralateral leg: 18.1 Nm) compared to the group using both strategies (8.4 Nm).

3.5. *Relationship between compensatory work and walking energy cost*

In 2 patients, the walking energy cost data were unrealistically low (2.53 and 3.14 J/kg/m, healthy reference value is 3.3 J/kg/m) and therefore excluded. There was no significant correlation between total positive joint work at FWS or positive work per meter at FWS and walking energy cost (at CWS) (total joint work: r = 0.433, $p = 0.122$, joint work per meter: r = 0.317, $p = 0.269$, based on n = 14 patients).

4. Discussion

We found that patients with unilateral flaccid calf muscle weakness and reduced ankle power had a slower CWS compared to healthy individuals, but did not dissipate more energy at contralateral heel-strike nor generate more lower limb joint work. However, at higher walking speed, matched with healthy controls, negative work at contralateral heel-strike was increased and patients compensated by generating additional work at the ipsilateral hip and/or contralateral knee and hip. While mechanical work at FWS and walking energy cost at CWS were both increased in our patients, they were not related.

At CWS, no increase in contralateral negative joint work and compensatory positive joint work was found, in contrast to previous studies in patients with unilateral reduced ankle power [13,28]. However, these patients did not have flaccid muscle weakness and walked considerably slower, which lowers the negative work at contralateral heel-strike and, consequently, the positive joint work requirements [13,16]. Likely, in accordance with the energy minimization hypothesis [29,30], reducing walking speed is a functional compensation to limit increases in lower limb joint work, therewith also limiting increases in the energy consumption of walking. Yet, patients still generated relatively more work at their hip and contralateral leg, as also seen in hemiplegic CP children [13,15]. The higher age of patients may have influenced the effects on CWS, however, CWS does not change between the age of 30 and 60 [31,32].

At FWS, negative contralateral joint work was increased, which was compensated for by an increase in ipsilateral positive hip work and/or contralateral positive leg work. Ipsilateral hip work was mainly increased during swing, probably to ensure the forward swing of the leg, as normally ankle push-off work is used for this purpose [10]. Compensations at the contralateral leg occurred at the hip and knee joint during mid-stance to counterbalance the increased energy losses during heel-strike [7,15], and during the swing phase to redistribute work across the legs to increase walking speed [15].

Although at FWS, we found that ipsilateral hip work and contralateral leg work were increased, 69% of the individual patients

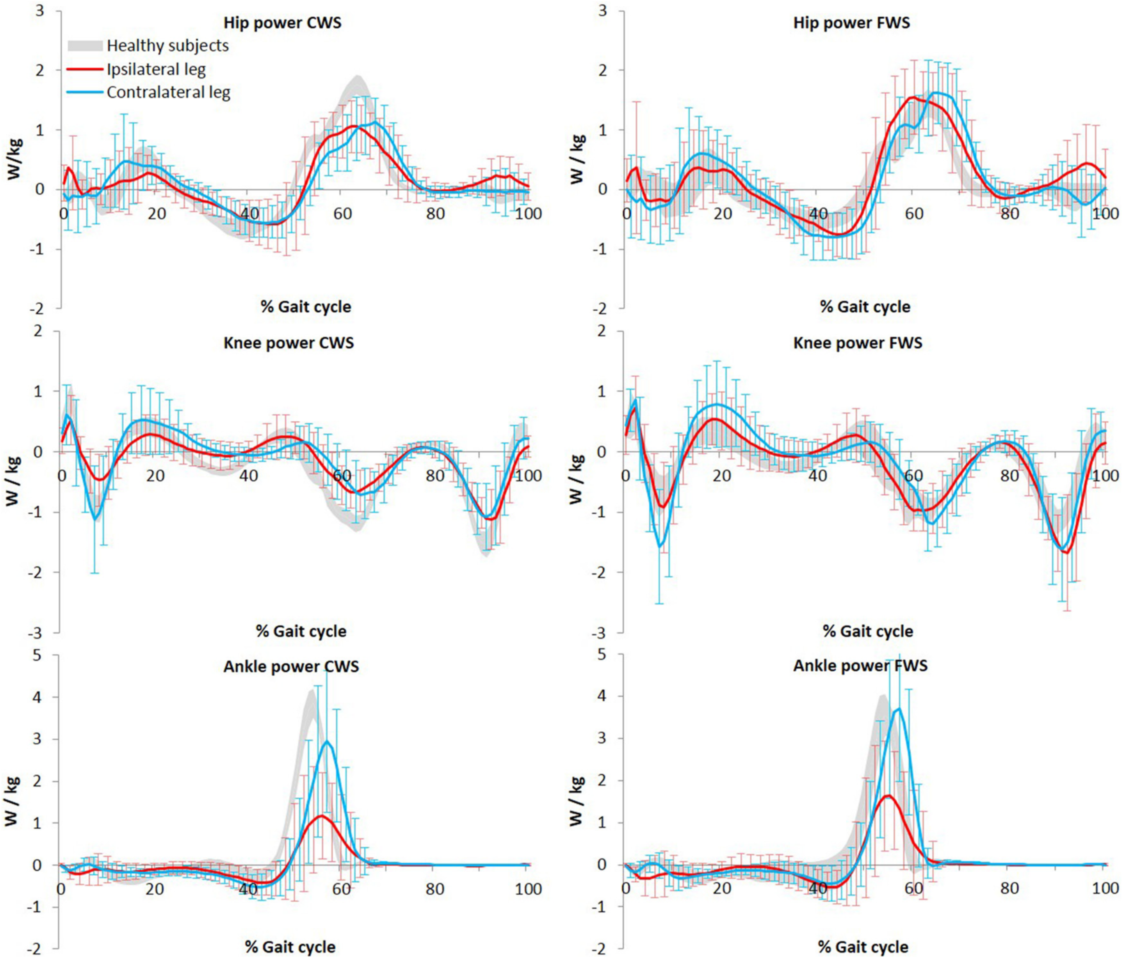

Fig. 1. Ankle, knee and hip power at CWS and FWS.

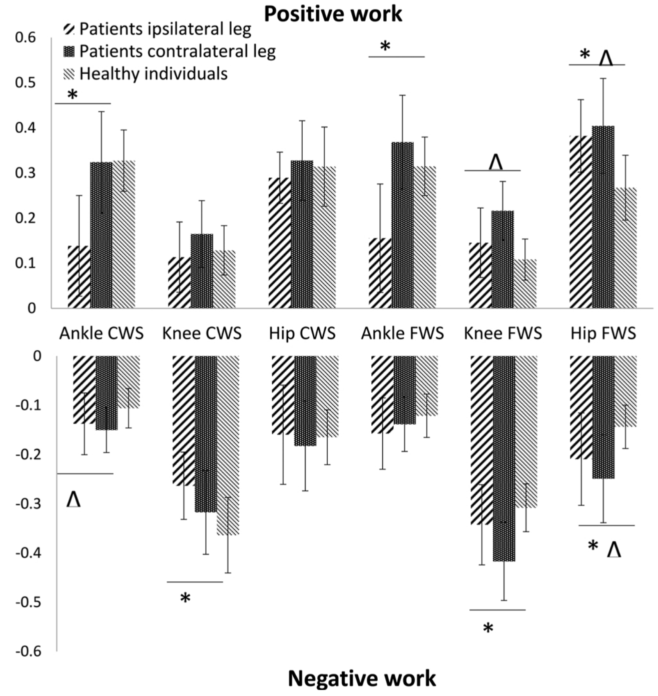

Fig. 2. Ankle, knee and hip work at CWS and FWS over the whole gait cycle.
*Denotes a significant difference between the ipsilateral leg and healthy individuals.
ΔDenotes a significant difference between the contralateral leg and healthy individuals.

compensated by solely using one of the compensation mechanisms. As shown in Table 2, patients using either strategy instead of both seem to have less profound plantar flexor weakness and generated less positive work over a full gait cycle at FWS, indicating that when less compensatory work is needed, patients only use one strategy.

That some patients used solely their ipsilateral hip as compensation and others their contralateral leg, may be caused by additional (relative) muscle weakness. The weaker dorsiflexors of the hip group induced the necessity of a pull-off strategy to avoid tripping, and, consequently, hip work in swing increases [33]. Additionally, the more unstable patients may have used this strategy as the hip strategy results in a more symmetrical gait pattern with a higher step frequency, as shown in a post-hoc analyses (ipsilateral vs contralateral steptime, hip group: 0.49 ± 0.05 vs 0.47 ± 0.03 s, leg group: 0.56 ± 0.04 vs 0.49 ± 0.05 s), which is a mechanism to increase medio-lateral balance [4,34]. Furthermore, some patients may not have had sufficient (relative) strength in their contralateral leg to compensate as this leg also suffered from the increased negative work at heel-strike. Consequently, these patients could only compensate with their ipsilateral hip [15,35]. Why exactly patients differ in compensation strategy and which strategy is most efficient should be further explored in this population

Compensating with the ipsilateral hip is hypothesized to be less energy efficient compared to compensating with the contralateral leg as it increases the energy dissipation at heel-strike [15], but in our study the walking energy cost were increased by 32% in both groups. Interestingly, the walking energy cost of the group using both strategies was only 19% increased despite higher work requirements. Yet, while the

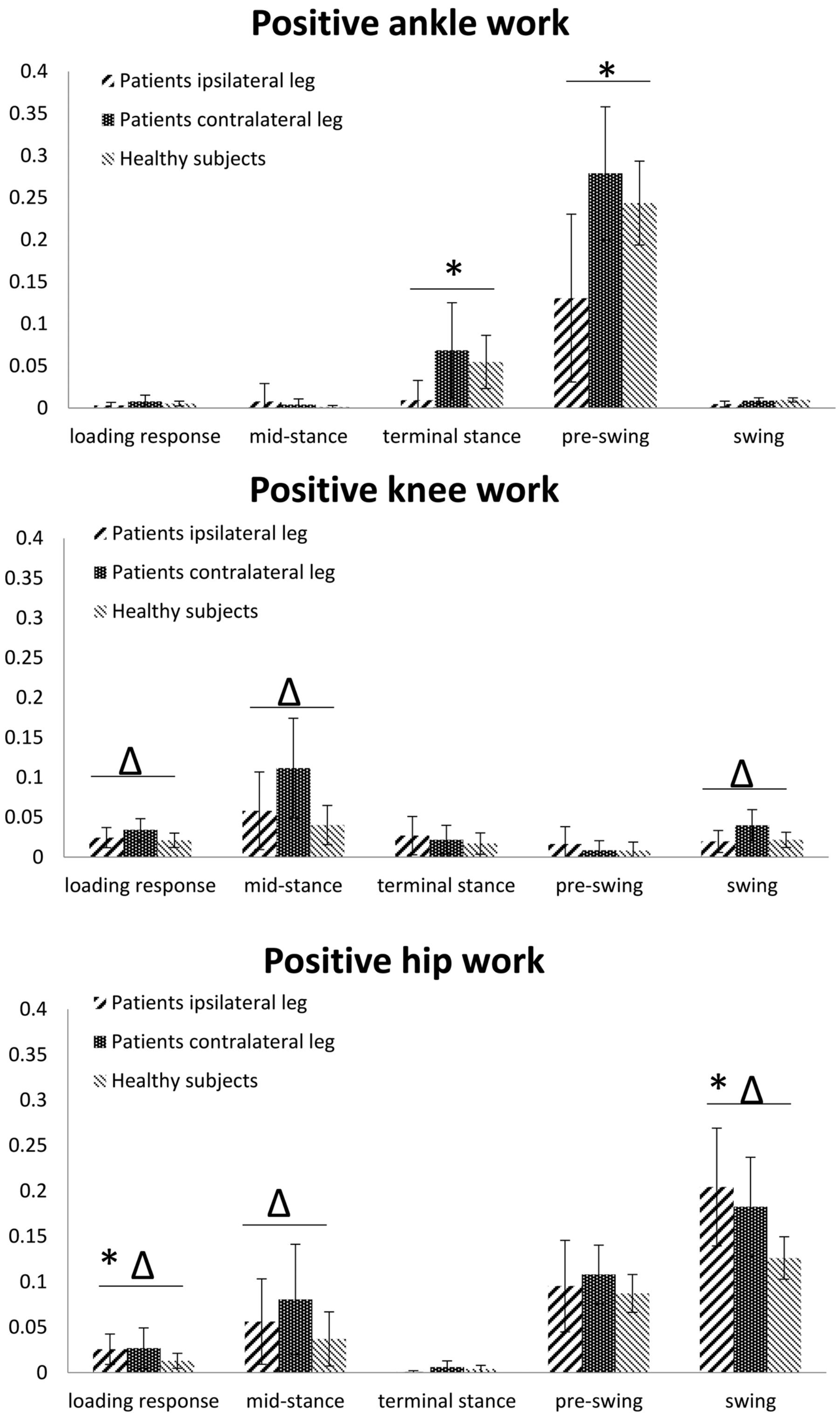

Fig. 3. Positive ankle, knee and hip work during the different gait phases at FWS.
*Denotes a significant difference between the ipsilateral leg and healthy individuals.
ΔDenotes a significant difference between the contralateral leg and healthy individuals.

mechanical work and walking energy cost were both increased in our patients, no relation between the two was found. In normal walking they are badly related [36] and apparently also in patients with calf muscle weakness. Possibly, the variation in distribution between ipsilateral hip work and contralateral leg work between patients led to heterogenity in muscle activation patterns, level of co-contraction and, consequently, compensation efficiency [37]. Future research should explore these hypothesis using musculoskeletal simulations. Alternatively, as shown in amputees, it might be that the step-to-step transition work better reflects the compensatory work needed to counterbalance the negative work and is more strongly related with walking energy cost [19,38].

A limitation of this study was that we did not measure arm swing or trunk movements, as these compensation have been reported in children with CP [39]. Furthermore, walking energy cost was only measured at CWS and, consequently, the efficiency of the compensation strategies at FWS could not be exactly determined. Also, the gait analysis was performed barefoot while walking energy cost was measured with shoes, which may have altered the gait biomechanics and work requirements during the energy cost measurement.

5. Conclusions

In conclusion, we showed that the functional mechanism of patients with unilateral flaccid calf muscle weakness to compensate for a reduced ankle push-off is to lower their walking speed. This reduces the energy dissipation at contralateral heel-strike and, consequently, no compensatory lower limb joint work needs to be generated. However, at higher walking speed, matched with healthy controls, energy dissipation is increased, and patients compensate for this by generating more positive work with their ipsilateral hip, contralateral leg or both. Patients with weakest plantar flexors used both strategies. Although mechanical work was increased in patients, this was not related with the elevated walking energy cost.

Conflict of interest

None to declare.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2018.08.016.

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