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Performance of stair negotiation in patients with cerebral palsy and stiff knee gait

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ABSTRACT

Background: Due to the limited knee range of motion, achieving adequate foot clearance while walking on level ground constitutes a major problem for patients with cerebral palsy and stiff knee gait. Stair negotiation as an activity of daily life requires a considerably higher knee range of motion than level ground walking, but little is known yet as to whether such patients are able to walk stairs.

Research question: The aim of this study was to investigate how patients with a limited knee range of motion negotiate stairs. Do they increase their peak knee flexion and use the same pattern as in walking on level ground? How do the muscles act during stair negotiation?

Methods: In this explorative study, 17 adults with bilateral, spastic cerebral palsy and stiff knee gait and 25 healthy subjects were examined. 3D motion analysis, including electromyography, was performed while walking on level ground, upstairs, and downstairs. A linear mixed model was used for between- and within-group comparisons.

Results: Walking upstairs and downstairs, patients increased their peak knee flexion by around 30° compared to level walking. Thus, increased knee flexion may be seen as the main mechanism for maintaining foot clearance on stairs. An increased pelvic obliquity (elevation) and hip flexion were also found and involved subjects showed a slight increase in rectus femoris activity when walking on stairs compared to level walking within the phases of high knee flexion.

Significance: This study showed that patients with cerebral palsy and stiff knee gait are able to flex their knees more than would be required for level walking. Hence, the patients are able to adapt their rectus activity to stair walking to some extent. Therefore, further investigations might help to open up new therapeutic options to facilitate level walking and stair negotiation in patients with stiff knee gait.

1. Introduction

Several studies have described how typically developed subjects (TD) negotiate stairs, which firstly give an impression of the demands placed on the locomotive system and, secondly, reveal mechanisms to conquer those demands [1–8]. Jevsevar et al. showed that 98.6° (ascending) and 90.3° (descending) peak knee flexion are needed to negotiate stairs, as compared to 64.6° on level ground [3]. McFadyen et al. claimed that the quadriceps femoris generates the greatest amount of energy during stair ascent, whereas both knee extensors and ankle plantarflexors are involved in absorbing a significant amount of energy during descent [9]. Those differences in level walking and stair walking caused Nadeau et al. to assume that mild restrictions in knee flexion can dramatically reduce functional performance in stair negotiation[7].

Due to the limited knee range of motion (ROM), achieving adequate foot clearance when walking on level ground constitutes a major problem for patients with bilateral, spastic cerebral palsy (BSCP) and stiff knee gait [10]. The causes of stiff knee gait are understood only in part. A prolonged activity of rectus femoris in swing is seen as the main cause for limited knee ROM [10–13]. Different compensatory mechanisms, such as contralateral vaulting, circumduction, and upward pelvic tilt, have been reported to increase foot clearance in level walking [10]. Nevertheless, patients often drag their foot, trip, or even fall [14].

Stair negotiation as an activity of daily life and part of the gross motor function classification system (GMFCS) [15] creates considerably higher demands on sagittal knee ROM [1]. Hence, knee function, which is already critical in stiff knee patients in level walking, must be improved for stair negotiation. Walking on level ground is generally

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considered as one of the most automatic and unconscious actions in daily life [16]. Walking on stairs, however, is a complex locomotive task, where the foot must be placed exactly, and thus a higher level of cognitive function and consciousness is required [17]. There are two different strategies to negotiate stairs: step-over-step and step-by-step [18]. Only few studies have reported on the management of daily life activities in patients with BSCP and stiff knee gait. When walking on uneven ground, patients with BSCP and stiff knee gait need to increase knee flexion in order to achieve adequate foot clearance [14]. Preliminary research in a small cohort has shown a significant decrease in sagittal knee range of motion during level walking in BSCP compared to TD, whereas it was not significantly decreased on stairs [19].

It is doubtful as to whether patients with BSCP and stiff knee gait can step out of the movement pattern they use when walking on level ground and whether these patients, especially those with stiff knee gait and who use walking devices on level ground, can manage stairs. Therefore, we aimed to investigate strategies for improving sagittal knee motion and possible facilitated mechanisms in this study. Furthermore, it is not known whether the muscle activity of knee extensors prevents sufficient knee flexion on stairs.

Therefore, our research questions were: Are such patients generally able to manage stairs? Are patients with stiff knee gait able to flex their knees sufficiently to walk on stairs? Do they use a similar pattern when walking on stairs as in level walking or are they able to step out of their movement pattern? How do they modify their muscle activity on stairs?

2. Material and methods

2.1. Participants

A total of 23 adults with BSCP and 25 TD subjects underwent a 3D gait analysis on level ground (LEVEL) and stairs (UP = upstairs and DOWN = downstairs). Inclusion criteria were: BSCP with stiff knee gait on at least one side, GMFCS [15] I-III, and age of majority. Stiff knee gait was identified according to Goldberg's criteria [14,20]: 1) peak knee flexion in swing, 2) reduced knee ROM from toe off to peak knee flexion, 3) reduced knee ROM over the complete gait cycle (GC), and 4) delayed peak knee flexion. At least three of four gait parameters had to be outside two standard deviations (SD, ±) of the values of TD. Exclusion criteria were: Additional neurologic or muscular diseases, structural pes equinus with absence of secondary heel strike, casting or intramuscular injections of botulinum toxin A [21] within the last 6 months, bony operation within the last year, and status post selective dorsal rhizotomy [22].

In all, 54 patients from the database of our gait laboratory fulfilled the inclusion criteria. The full recruiting process is depicted in Fig. 1. Of 44 patients contacted, 43 were able to negotiate stairs. In total 23 patients participated in this study, and 6 of 23 patients were ultimately excluded: One patient no longer fulfilled the stiff knee gait criteria and five patients used the step-by-step strategy [18] in at least one condition. Three of the included patients were only unilaterally stiff-legged; thus, in total 17 patients (7 male, 10 female) and 31 stiff legs, respectively, were included in the analysis.

Patients' mean age was 34.3 ± 9.7 years and mean BMI 23.9 ± 4.0 kg/m^2. One patient was classified as GMFCS I, 13 as II, and 3 as III. In all, 25 TD subjects (mean age 31.8 ± 11.8 years; mean BMI 23.6 ± 2.7 kg/m^2; 13 male, 12 female) without neurologic or orthopedic diseases participated as the control group. The ethics committee of Heidelberg University approved the protocol (S-398/2013) and all subjects gave their written consent.

2.2. Measuring system and procedure

All participants performed a gait analysis at a self-selected walking speed while wearing their own shoes. The stair setting consisted of five steps (height 15 cm, depth 32 cm, and width 100 cm) and a handrail on both sides (height 97 cm). Patients were free to use the handrail and other self-brought walking devices. Kinematic data were collected via a 12-camera Vicon System (Vicon Inc., Oxford, UK) using the Plug-in-Gait model. Surface electromyography (EMG) of the rectus femoris and vastus lateralis was performed using a Myon System (Myon AG, Schwarzenberg, Switzerland).

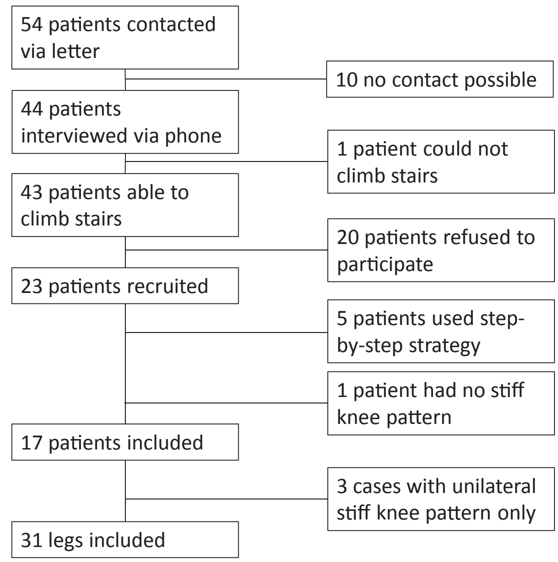

Fig. 1. Flow chart about the recruitment process.

2.3. Data processing & statistical analysis

In addition to step time (time from initial contact of one foot to initial contact of the opposite foot [23]) and peak knee flexion during the complete gait cycle, peak pelvic obliquity, peak hip flexion, peak hip abduction, and peak knee flexion were calculated in swing phase to monitor the mechanisms of toe clearance. The peak ankle plantarflexion was calculated in stance to assess contralateral vaulting.

EMG data was bandpass filtered (20–350 Hz), normalized for each GC individually to 100% and averaged across trials (at least 5 valid trials per condition), enveloped, and integrated over the GC. The EMG data for one leg in level walking, one in walking upstairs, and five in walking downstairs were excluded due to technical shortcomings or data artifacts. The corresponding kinematic data were still included. The pattern characteristics are presented descriptively by visual analysis of the curves. To evaluate the muscular activation in phases of high knee flexion (LEVEL: initial swing, mid-swing; UP: mid-swing, terminal swing; DOWN: pre-swing, initial swing) and to compare it between the conditions, the mean muscle activity in those phases was calculated for each condition and a within-group comparison of BSCP-group was drawn.

The knee flexion velocity (KFV), calculated as the first derivation of knee flexion with respect to time (s), and the muscle activity were evaluated to show any possible influence on decreased knee flexion.

Descriptive statistics, including means and SD, were calculated for each parameter (IBM SPSS Statistics 23, New York, USA). All stiff legs were analyzed - both legs of 14 patients and one leg of three patients. To consider the dependence of both legs on the same person the linear mixed model was chosen. It was used for between-group comparisons (BSCP versus TD) and within-group comparisons of the conditions LEVEL, UP, and DOWN. A significance level of $p < 0.05$ was adopted and the resulting data were tested for normal distribution.

3. Results

Forty-three of 44 patients stated that they were able to negotiate

Table 1
Mean and SD of temporo-spatial parameters and kinematics in patients (BSCP) and healthy subjects (TD) in all conditions (LEVEL, UP, DOWN). GC = gait cycle.

Conditions	BSCP			TD		
Parameters	LEVEL	UP	DOWN	LEVEL	UP	DOWN
Step time [s]	0.6 ± 0.2 [*,a,b]	1.2 ± 0.6 [*,a]	1.5 ± 0.8 [*,b]	0.5 ± 0.1 [a]	0.6 ± 0.1 [a,c]	0.6 ± 0.1 [c]
Intraindividual SD of step time [s]	0.04 ± 0.03 [*,a,b]	0.13 ± 0.10 [*,a]	0.16 ± 0.11 [*,b]	0.01 ± 0.01 [a,b]	0.03 ± 0.01 [a]	0.03 ± 0.01 [b]
Peak pelvic obliquity (elevation) in swing [°]	2.0 ± 2.8 [a,b]	5.2 ± 4.1 [a]	4.0 ± 4.7 [*,b]	1.2 ± 1.6 [a]	5.9 ± 2.0 [a,c]	1.8 ± 1.7 [c]
Peak hip flexion in swing [°]	40.7 ± 6.4 [*,a,b]	67.3 ± 8.1 [a,c]	45.3 ± 7.6 [*,b,c]	35.7 ± 6.3 [a,b]	64.3 ± 6.4 [a,c]	41.9 ± 6.9 [b,c]
Peak hip abduction in swing [°]	1.6 ± 5.5 [*,a]	4.4 ± 5.4 [*,a,c]	1.6 ± 5.4 [*,c]	8.9 ± 2.8 [a,b]	7.7 ± 2.9 [a,c]	5.8 ± 2.9 [b,c]
Peak knee flexion in swing [°]	43.7 ± 7.5 [*,a,b]	74.2 ± 11.6 [*,a]	76.9 ± 6.3 [*,b]	64.0 ± 4.2 [a,b]	87.7 ± 5.8 [a]	88.6 ± 5.4 [b]
Peak knee flexion in GC [°]	43.7 ± 7.5 [*,a,b]	74.2 ± 11.6 [*,a]	81.9 ± 6.5 [*,b]	64.0 ± 4.2 [a,b]	87.7 ± 5.8 [a]	88.6 ± 5.4 [b]
Peak knee flexion velocity in swing [°/s]	119.0 ± 57.7 [*,a]	171.6 ± 66.2 [*,a,c]	101.9 ± 40.7 [*,c]	351.2 ± 29.7 [a,b]	392.7 ± 69.3 [a,c]	299.0 ± 51.4 [b,c]
Peak ankle plantarflexion in stance [°]	1.7 ± 10.5 [*]	2.9 ± 9.3 [*]	3.1 ± 10.9 [*]	19.7 ± 6.1 [a,b]	14.5 ± 6.3 [a]	15.9 ± 6.3 [b]

* Between-group comparison: significant difference between BSCP and TD ($p < 0.05$).
[a] Within-group comparison: significant difference between LEVEL and UP ($p < 0.05$).
[b] Within-group comparison: significant difference between LEVEL and DOWN ($p < 0.05$).
[c] Within-group comparison: significant difference between UP and DOWN ($p < 0.05$).

stairs in daily life. Two of 17 examined patients with stiff knee gait used self-brought devices in level walking: one used 2 crutches and one an anterior walker.

One patient used no handrail, 6 patients on one side, and 8 patients on both sides in UP and DOWN. Two patients showed a mix of handrail use in UP and DOWN: 1) no handrail UP and on one side DOWN, 2) on one side UP and on both sides DOWN. No patient used their self-brought walking devices for walking on stairs.

3.1. Upstairs

Regarding UP, the step time in patients was increased twofold compared to TDs in UP and to level walking in BSCP (Table 1). The BSCP group demonstrated a threefold increased intra-individual SD of the step time, comparing UP to LEVEL.

The peak KFV in BSCP when walking upstairs was significantly increased by about Δ53°/s compared to level walking (Table 1).

When walking upstairs, a significant increase in pelvic obliquity (elevation; Δ3.2°), hip flexion (Δ26.6°), and hip abduction (Δ2.8°) as compared to level walking was found in BSCP (compare Fig. 2). Peak knee flexion in swing in patients was significantly higher for UP than for LEVEL. BSCP showed a higher increase in peak knee flexion in swing on stairs than TDs. Walking upstairs, the BSCP showed a significantly decreased hip abduction, increased knee flexion, and decreased plantarflexion compared to TD.

By visual comparison of the EMG curves (Fig. 3), the muscular activity pattern in BSCPs during ascent shows considerable differences compared to TDs: The initial activity in rectus femoris and vastus lateralis was reduced and, in particular, the rectus femoris showed an almost continuous activity with a low range in full gait cycle (Fig. 3). Compared to the EMG while walking upstairs, the muscle activity in patients appeared more similar when walking downstairs or on level ground compared to TDs. The patients showed a slightly increased mean of rectus femoris activity within the phases of high knee flexion while walking upstairs (71%, $p = 0.312$) compared to walking on level ground (63%). Mean of vastus lateralis was significantly decreased when walking upstairs (26%, $p = 0.033$) compared to level ground (34%).

3.2. Downstairs

The patients showed a 2.5- to 3-fold higher step time in DOWN than TDs and an approx. 2.5-fold increased step time comparing DOWN to LEVEL (Table 1). The within-group comparison (DOWN vs. LEVEL) of the intra-individual SD in patients' step time showed a fourfold increase.

The peak KFV when walking downstairs showed a nonsignificant decrease of Δ17°/s compared to LEVEL (Table 1).

Furthermore, pelvic obliquity (elevation), hip flexion, and knee flexion in DOWN were higher than in level walking in BSCP. The knee flexion while walking downstairs increased about 1.75-fold in BSCP and about 1.4-fold in TD compared to level walking. The BSCP demonstrated a significantly increased (DOWN vs. LEVEL) pelvic obliquity (elevation) and hip flexion and a decreased hip abduction, knee flexion, and plantarflexion compared to TD. The peak knee flexion during the gait cycle was significantly increased in patients while walking downstairs compared to level walking.

In BSCP, the mean of rectus femoris while walking downstairs (68%, $p = 0.524$) was slightly increased compared to level walking (63%). A significant increase was found in the mean of vastus lateralis when walking downstairs (43%, $p = 0.050$) compared to walking on level ground (34%).

4. Discussion

It is remarkable that patients with BSCP and stiff knee gait were actually able to negotiate stairs rather well. Of 44 interviewed patients, 43 stated that they are able to negotiate stairs in daily life. Surprisingly, only 5 of 23 examined patients then used the step-by-step strategy and 18 the step-over-step strategy, which places higher demands on the patient. The knees were flexed sufficiently to walk on stairs. However, most patients used the handrail uni- or bilaterally: notably, often only a one-sided handrail exists in public places. Despite their impaired knee flexion, even the patients with GMFCS III were able to negotiate stairs using the step-over-step strategy in ascent and descent.

Considering the kinematics, the joint motions of the CP group began to approach the motion of the TDs when walking on stairs, downstairs more than upstairs. The maximum knee flexion in patients is almost the same as in TDs. A statistically significant difference was observed; however, it is not clinically relevant. This might be associated to the higher level of consciousness that is necessary for stair walking (e.g., for foot placement) [17]. Of course, it must be considered that BSCP show an immense increase in step time on stairs compared to TD on stairs and BSCP in LEVEL.

Furthermore, all patients showed an increase in peak knee flexion in UP and DOWN, although the absolute value is still lower than that for TDs. Interestingly, peak knee flexion in BSCP on stairs is higher than required for normal level walking. Apparently, therefore, the patients would be able to bend their knees adequately for normal level walking (referring to knee flexion). One strategy to manage stairs is simply to walk slower, and the step time represents the higher demand of stairs and the difficulties for BSCP in negotiating those demands. Walking on level ground is generally considered to be one of the most automatic and unconscious actions of daily life [16] and the extreme increase in

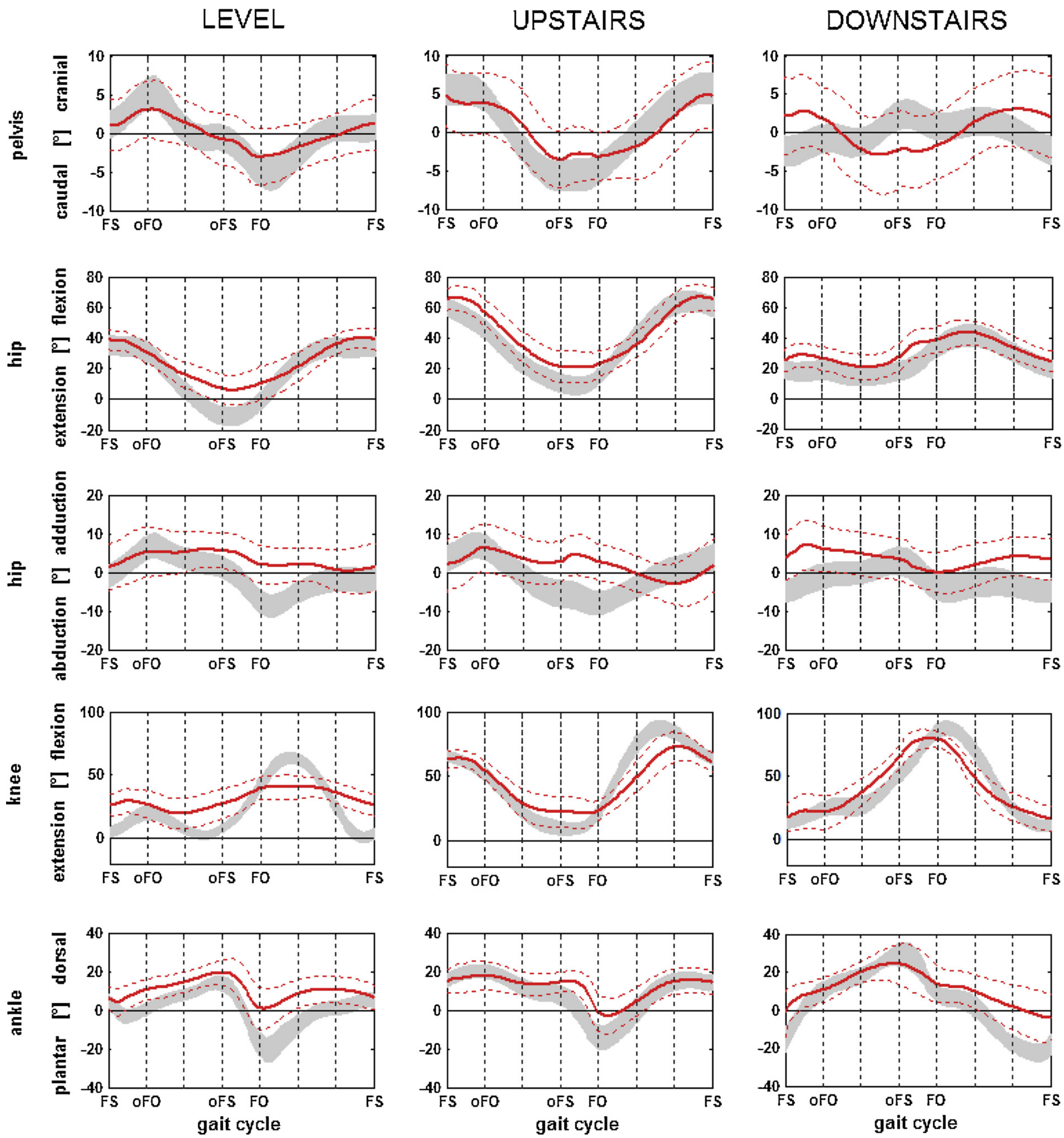

Fig. 2. Kinematics in conditions LEVEL, UPSTAIRS and DOWNSTAIRS normalized by sub-phases of the gait cycle in patients with BSCP (red; mean in continuous lines, one SD in broken lines respectively) and TD (mean ± one SD in grey bandage). FS = foot strike, oFO = opposite foot off, oFS = opposite foot strike, FO = foot off.

intraindividual SD of step time in walking on stairs indicates, in particular, that patients may walk on stairs less automatically and with a higher level of consciousness. The additional time allows them to set the foot more accurately on the step and to increase the knee flexion required to prevent them from tripping or falling on stairs. An interaction between attention for movement execution and postural control in children with BSCP has been shown [24], and higher levels of attention and consciousness than for level walking might possibly also affect the performance in stair negotiation.

4.1. Upstairs

To manage walking upstairs and to achieve adequate foot clearance, patients and TD alike used increased pelvic obliquity (elevation), hip flexion, and knee flexion, whereas only BSCP increased hip abduction in ascent compared to LEVEL. BSCP showed a higher increase in knee flexion and hip abduction (comparing UP to LEVEL) than TD did. Circumduction seemed to cause only a small increase in foot clearance as there is little movement in hip abduction and it must be presumed that increasing knee flexion is an important factor for maintaining foot clearance in walking upstairs in patients with stiff knee gait. Similar findings were reported for gait on uneven surfaces [14]. Nevertheless, due to the many degrees of freedom in the distal locomotor unit (hip, knee, and ankle) and due to the long lever arm (concerning the hip joint), it is possible that, although each factor shows only a small increase (e.g., $\Delta +2.8^{\circ}$ in hip abduction) or is not significantly altered, the sum of all mechanisms results in a significant shortening of the functional leg length.

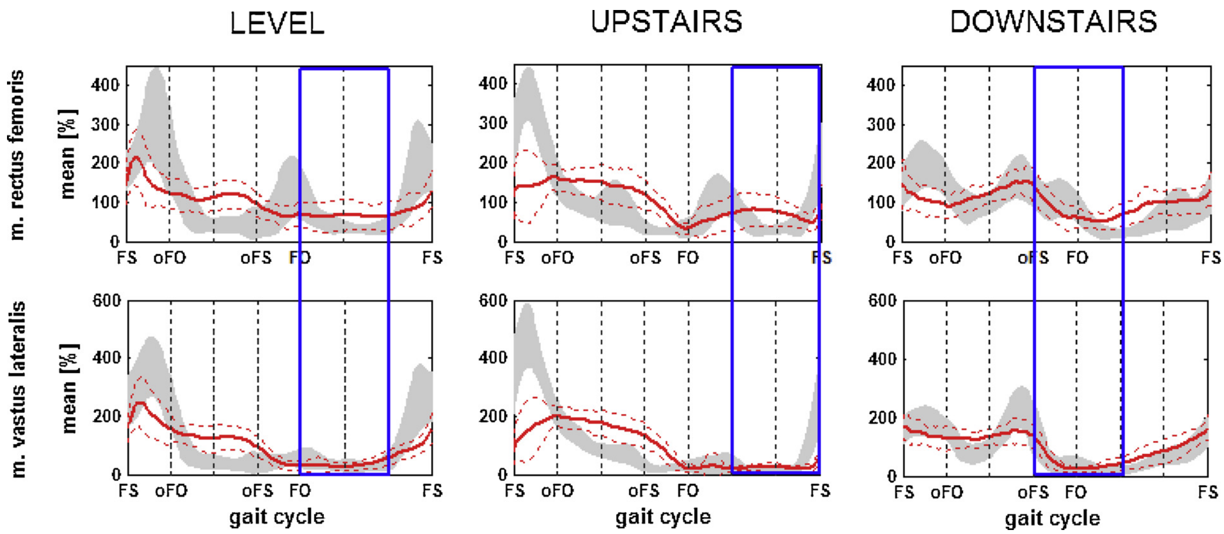

Fig. 3. EMG in conditions LEVEL, UPSTAIRS and DOWNSTAIRS normalized to the gait cycle in patients with BSCP (red; mean in continuous lines, one SD in broken lines respectively) and TD (mean ± one SD in grey bandage). FS = foot strike, oFO = opposite foot off, oFS = opposite foot strike, FO = foot off. Boxes indicate phases of high knee flexion.

Hip flexion was increased in times of peak knee flexion. Thus, it is conceivable that the rectus femoris was in a more relaxed state, which makes it easier for stiff-knee-gait patients with a spastic rectus femoris to bend the knee. The patients who showed decreased knee flexion when walking on level ground were in fact able to bend their knees in swing phase without the external force of body weight (as in downstairs). The plantarflexion was slightly increased while walking upstairs compared to level walking, which may be taken as a sign of vaulting.

Although peak KFV was significantly higher in walking upstairs than in level walking, the rectus femoris did not show a significant increase in activity in phases of high knee flexion. As the rectus femoris is a two-articulated muscle, increased hip flexion may allow for increased KFV without an increase in muscle activity, too.

Furthermore, in ascent, rectus femoris and vastus lateralis both show characteristically high standard deviations in their activity in loading response (comp. Fig. 3), indicating that individually different activation patterns might be present for coping with the high demand of stair walking. Perhaps specific and varied muscle activation patterns address different underlying compensation mechanisms which were not assessed in this cohort analysis. Further research should investigate in more detail the different muscle activation patterns and their impact on kinematics.

4.2. Downstairs

The sagittal knee pattern in BSCP when walking downstairs was very close to that of the TD. The peak knee flexion occurred at the end of the stance phase in BSCP, but at the beginning of swing phase in TD. The patients may use their body weight to allow an additional external flexion moment to act on the knee joint in descent [1] and, accordingly, bend their knee more than they are able to do with intrinsic forces (e.g., muscle power). Sufficient knee flexion and dorsiflexion in the stance leg were required due to a cranially tilted pelvis and an insufficient plantarflexion at initial contact in the swing leg to put the foot onto the lower step.

When walking downstairs, the rectus femoris and vastus lateralis both showed slightly increased muscle activity in the phase of peak knee flexion, i.e., in stance, compared to level walking. The body weight acted as an externally flexing moment on the knee. The knee extensors had to react to it using eccentric muscle work. Indeed, the higher activity in vastus lateralis might be due to a late controlled lowering and provide stability in the knee joint [13].

4.3. Limitations

Only about 50% of all contacted patients participated in this study. It was rather surprising how well these patients managed stairs but we do not have detailed information about the stair walking ability of the other half as we did not pose any detailed questions in the phone interviews for recruitment.

It must be considered that this study was performed with a heterogeneous group of only 17 adult patients, ranging from GMFCS I-III, who had all received different kinds of surgical treatments that in some cases affect the knee (e.g., rectus femoris transfer [25]). A larger number of patients and a detailed analysis of the type of surgeries performed, for example, could provide more specific information about whether surgery can improve stair negotiation.

Furthermore, we had no measuring system on the handrail to detect the amount of weight bearing by the arms and the handrail while walking on the stairs. Some patients just touched the handrail whereas others used it to pull themselves upstairs.

5. Conclusion

Patients with BSCP and stiff knee gait were able to negotiate stairs and frequently did so in their daily life, although they face greater difficulties than TD. When walking stairs, the patients bend their knees more than would be required for normal walking on level ground. The rectus femoris was able to adapt in phases of peak knee flexion. Larger variations in muscle activation in loading response indicate different movement strategies that should be investigated further.

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Conflict of interest statement

None to declare.

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