A Pilot Study to Examine the Activity of Primary Plantar Flexor Muscles using an Electric Motorized Treadmill in Comparison to Overground Walking

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Abstract: The gait during overground (OG) and treadmill (TM) walking was already investigated by different scientific groups. Differences in the muscle activation and in the kinetics were found. The aim of the present examination was to find conditions for a comparable or higher activation of the plantar flexor muscles during TM walking in order to give recommendations for training and rehabilitation. A pilot study with different conditions (e.g. with and without inclination) was done. Furthermore, the aspect of different walking velocities in OG and TM walking was investigated. The self selected speed was reduced during TM walking (1.1 km/h). Regarding the muscle activation, it is recognizable that the primary plantar flexor muscles react similarly. The activation is reduced during TM walking. Based on the inclination of 1.5 %, a little larger activity during TM walking is observed for the muscles M. gastrocnemius medialis and lateralis. Our results confirm that there are differences between OG and TM walking in the activation of the primary plantar flexor muscles. The results indicate that there is an effect of different, adjustable conditions (speed and inclination). Further examinations are planned to find detailed information about the different conditions and their impact on the muscle activation.

1 INTRODUCTION

Treadmills are used in the fields of sport and rehabilitation due to the required space for walking/running large distances. That is why a treadmill is often used for the repetitive exercise of walking in rehabilitation routines or for training aspects in order to pass longer distance with a defined speed. The applied treadmills are mostly electric motorized treadmills. The person, who is walking on the treadmill, is to some extent moved by the motor which is integrated in the treadmill. However, on the market there are also self-powered treadmills, so called manual treadmills. Using such a treadmill, the motion during walking is created by the muscle strength of the running or walking person. In spite of this offer, in most institutions, electric motorized treadmills are available and used for walking.

In patients with cerebral palsy (CP) the plantar flexor muscles are weakened, and gait deviations exist. CP occurs in different types, for example, the dropped foot (Type 1) or the equine foot (Type 2A) (Tugui and Antonescu, 2013). The gait of patients with an equine foot has a spasticity in the primary plantar flexors, the muscles M. gastrocnemius medialis and lateralis and M. soleus. Furthermore, a spasticity in the M. tibialis posterior is present. Due to that spasticity, the plantarflexion cannot be executed in an adequate way. Following the gait of these patients is characterized by walking on the tiptoes because the gait cycle (stride) is not initiated by the heel strike. The different phases and subphases of the gait of CP patients are impaired and do not proceed as described for the physiological gait (Perry and Burnfield, 2010; Whittle, 2007). The aim of therapeutic interventions is to strengthen these plantar flexor muscles and harmonize the gait in order to prevent secondary diseases. For that reason, a treadmill is used in a physiotherapeutic intervention to improve the gait of CP patients by repetitive walking.

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Oliveira et al. (2016) investigated the muscle activation during overground (OG) and treadmill (TM) walking. Their results confirm that there are differences in the muscle activation in both scenarios (Oliveira et al., 2016). The M. soleus showed a larger activation in terms of a higher peak and a larger integral during overground walking. In contrast to the activation of the M. soleus, the M. gastrocnemius medialis is more activated in the treadmill setting. The M. gastrocnemius lateralis reacted neither as the M. soleus nor as the M. gastrocnemius medialis. This muscle has a larger peak for the treadmill setting, but a larger integral for the overground setting. Van der Krogt et al. (2015) found differences in the kinetics of children with CP in OG and TM walking (van der Krogt et al., 2015).

During sport training sessions treadmills are used for warmups, cooldowns, running independetly from the weather conditions or for fitness aspects. Indeed, strengthing the muscles of the lower limbs is not the primary focus of the athletes. Nevertheless, the question of muscle activation during walking on the treadmill with different conditions (e.g. velocity and inclination) is also interesting to sportsmen and coaches. That's why the current pilot study focuses on the difference between overground and treamill walking with the main focus on muscle activity of primary plantar flexor muscles. In addition, the difference of walking velocity during OG and TM walking is considered.

Due to these two main topics two hypotheses are investigated. The first belongs to the muscle activity during TM walking in comparison to OG walking. It is assumed that the muscles are less activated during TM walking than during OG walking due to the motorization of the TM. The second hypothesis refers to the comfortable walking speed in both walking scenarios. It is assumed that during TM walking the person chooses a lower comfortable walking speed than in OG walking.

Regardless of the aspects that have to be considered by using treadmills in therapeutic settings, there are different, important issues for athletes. Consequently, an examination with healthy subjects was performed to prove the assumption that the plantar flexor muscles are less activated during TM walking. Furthermore, the aim of the conducted examination was to find conditions for a comparable or even higher activation of the muscles during treadmill walking.

2 METHODS AND MATERIALS

Different tests were done to prepare the pilot study and to find out which TM settings (speed and inclinations) are recommendable. The literature describes a reduced velocity on the TM for runners (Arsenault et al., 1986; Nymark et al., 2005; Kong et al., 2012; Marsh et al., 2006). During own tests, this fact was also noticed for the walking on a TM. Due to the motorization, the comfortable, self-selected speed during TM walking is perceived differently. For that reason, an additional investigation was done with 21 subjects (14 f, 7 m, age: 28.9 ($\pm$ 9.1) years) to quantify the speed difference of both settings. First, the self-selected speed for each subject was determined by the OG setting based on four 20m walking trials. The mean velocity was calculated. Subsequently, the comfortable speed during TM walking was determined in two trials starting once with a continuous increase of speed from a slow velocity (0.5 km/h) and once with a continuous decrease of speed from a fast velocity (7.0 km/h). The order was applied in a randomized way.

The gait of 23 young and healthy subjects (8 male, 15 female, age: 25.6 ($\pm$ 5.4) years, height: 170 ($\pm$ 10) cm, weight: 69.0 ($\pm$ 13.0) kg) was examined. The activation of the muscles M. soleus (SO), M. gastrocnemius medialis (GM) and lateralis (GL), the primary plantar flexor muscles, was registered using EMG-sensors with an 8-channel measuring device of biosignalplux (Plux Wireless Biosignals S.A., Lisbon, Portugal). In order to guarantee a stride-based analysis of the muscle activation, the gait was additionally captured using two 3D-accelerometers. These sensors were fixed on each heel in order to detect the heel strike as the initial event of the gait cycle.

In the OG setting the subjects passed six trials of a 40 m straightforward distance. They were asked to choose their comfortable walking speed during OG walking which was registered for each trial. Based on the noticed walking speed of the six OG trials the mean value was determined. Following the OG setting, each subject passed two walking trials on the TM, one without inclination (TM1) and another with an inclination of 1.5 % (TM2) following the recommendations of the literature (Jones and Doust, 1996; Heck et al., 1985; Vanhelst et al., 2009). Each of the TM trials has nearly the same length as all OG trials together to guarantee the almost the same amount of gait cycle in both settings are registered. Furthermore, a 1 km/h reduced speed was chosen for the TM trials based on the literature (Kong et al., 2012; Marsh et al., 2006) and own examinations (see results below). A randomization of the testing order could not be performed due to the adjustment of the TM speed

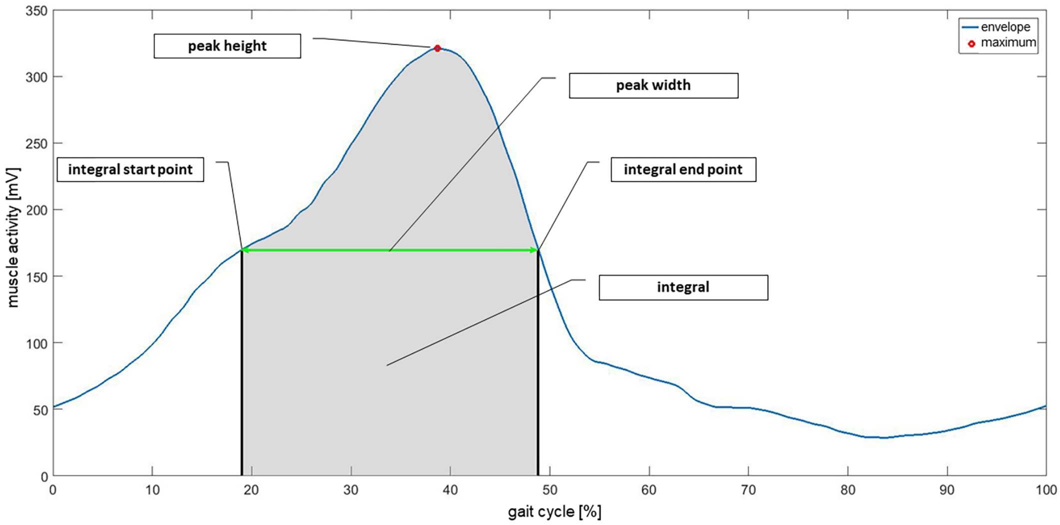


Figure 1: The mean EMG curve and marked the four calculated parameters: peak height (x and y), peak width and the integral.

which results from the OG setting.

Data Processing

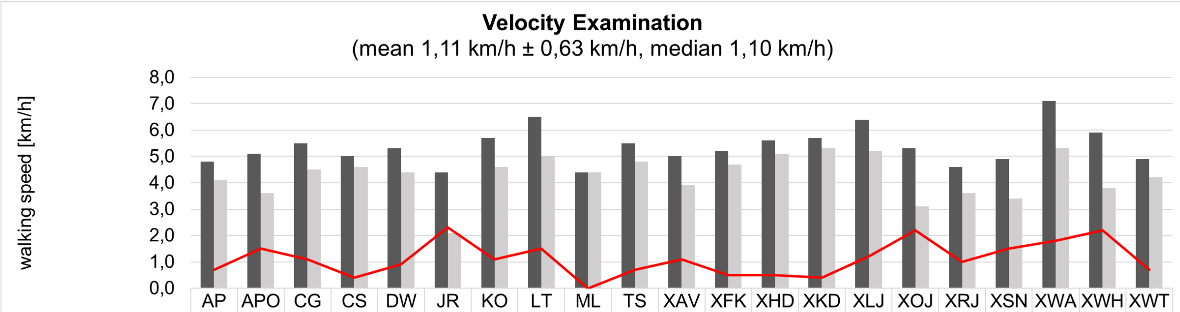
Based on the detection of the gait cycle the stride-based activity of the muscles can be determined, and the mean EMG signal can be calculated after an appropriate filtering, rectification of the signal and the calculation of the envelope curve by using the root mean square (RMS) (Pfeifer et al., 2003). A finite impulse response (FIR) bandpass filter 1000^{th} order with a frequency bandwidth of 20 - 300 Hz was used for filtering the raw EMG signals (Criswell, 2011; Miller et al., 2012; Mitchell et al., 2015).

Data Analysis

Four parameters were calculated for each setting (OG, TM1 and TM2) as visualized in figure 1. The peak height as the maximum of the average EMG signal in terms of the temporal occurrence (in percent of the gait cycle) and the amplitude (peak height in mV). In addition to the peak height, the peak width and the integral under the curve (EMG signal) was calculated. For calculating the peak width and the integral, two points have to be detected in the mean EMG curve. These two points, the integral start and end point, are located on the EMG curve at 50 % of the peak height (detected maximum of the EMG), see figure 1.
These parameters were analyzed descriptively and regarding significant differences. For the descriptive analysis, the mean value of the OG and TM muscle activity from all trials and all subjects, the mean difference between OG and TM (OG vs. TM1, OG vs. TM2) as well as the percentual quotient between OG and TM walking (TM1 or TM2) was calculated. Concerning the parameter peak height, a value smaller than 100 % indicates a lower activation of the plantar flexor muscles during TM walking.
The whole analysis (preprocessing, heel strike detection, calculation of mean EMG curve and parameters, statistical analysis) was done in MATLAB (TheMathworks Inc., Natick, MA, USA). The calculated parameters were tested for normal distribution by using the Kolmogorow-Smirnov test. Paired students t-tests were used for parameters with normal distribution (Atkinson and Nevill, 1998). The level of significance was set to $\alpha = 0.05$ for the above-mentioned statistical tests.

3 RESULTS

The results of the preliminary walking speed investigations are presented in detail with a bar chart in figure 2 as well as using a boxplot for summarizing the data of all subjects (figure 3). The mean speed for each subject in each setting is depicted in the bar chart (see figure 2). Furthermore, the diagram included the difference of the mean speed (OG and TM) as a red graph. Variations around 1 km/h are recognizable. The overall mean is 1.1 km/h with a standard deviation of 0.6 km/h. The differences in walking speed of both scenarios are clearly visible in the boxplot (see figure 3). The presented median values of the OG and TM walking show significant difference. Noticeable is the shape of the boxplots which varies clearly.
The examination of the muscle activity during OG and TM walking dedicates the four parameters: maxi-



	AP	APO	CG	CS	DW	JR	KO	LT	ML	TS	XAV	XFK	XHD	XKD	XLJ	XOJ	XRJ	XSN	XWA	XWH	XWT
mean overground	4,8	5,1	5,5	5,0	5,3	4,4	5,7	6,5	4,4	5,5	5,0	5,2	5,6	5,7	6,4	5,3	4,6	4,9	7,1	5,9	4,9
mean treadmill	4,1	3,6	4,5	4,6	4,4	2,1	4,6	5,0	4,4	4,8	3,9	4,7	5,1	5,3	5,2	3,1	3,6	3,4	5,3	3,8	4,2
difference	0,7	1,5	1,1	0,4	0,9	2,3	1,1	1,5	0,0	0,7	1,1	0,5	0,5	0,4	1,2	2,2	1,0	1,5	1,8	2,2	0,7

Figure 2: The registered mean velocity for both settings (overground in dark grey and treadmill in light gray) and each of the 21 subjects is given as bar chart. The difference between both settings is presented as red curve. In addition, the values are given below the chart and the mean and median velocity is stated.

mum peak (height, the amplitude in mV and temporal occurrence in percent), the peak width and the integral (the area under the curve). The determined values are presented in the following tables 1 - 3. Comparing all the values for the three examined muscles, it is recognizable that the primary plantar flexor muscles react similarly and a reduced activation during TM walking exist.

The TM gait without inclination causes a lower activity of all three muscles in comparison to the OG walking. The calculated difference for the parameter peak height (amplitude in mV) with negative values as well as the quotient with values smaller than 100 % confirm that fact quantitatively (GM: 83.9 %, GL: 75.5 %, SO: 68.9 %). Based on the used inclination of 1.5 %, a little larger activity during TM walking (TM2) is observed for the muscles GM and GL (GM: 91.3 %, GL: 79.6 %), but a similar or even larger activation could not be achieved with the chosen inclination.

The determined parameter peak width is always smaller for the OG walking resulting in negative difference and percentual values above 100 % (see table 1 - 3). The chosen inclination shows an effect to the parameter peak width. The value determined for the TM2 scenario is smaller than that calculated for the TM1 scenario (GM: 113.6 % vs. 105.4 %, GL: 145.8 % vs. 125.6 %, SO: 148.4 % vs. 129.3 %).

Considering the parameter integral under the curve (under the peak) the difference is always negative, and the quotient is smaller than 100 %, but no uniform behavior can be registered. The muscles GL and SO show a reduced activation during the TM2 scenario (with the 1.5 % inclination) compared to TM1 setting (without inclination) (GL: 99.9 % vs. 95.7 %; SO: 96.4 % vs. 86.4 %), while the integral of the muscle GM increases (GM: 94.0 % vs. 96.3 %).

All the parameters and the found differences are further investigated using t-test regarding significant differences. As marked in the tables below the differences are significant. The calculated correlation coefficient also confirms this significant difference with values smaller than 0.5 showing no good agreement.

Additionally, the temporal occurrence of the maximum peak was determined and considered in the investigation. This parameter shows no significant difference between the compared settings ($p > 0.05$) with moderate to high correlation coefficient ($r = [0.66, 0.92]$) for the small differences between the mean of OG and TM setting ranging from -0.77 to 0.45 % (see mean difference of the parameter peak occurence in tables 1 - 3).

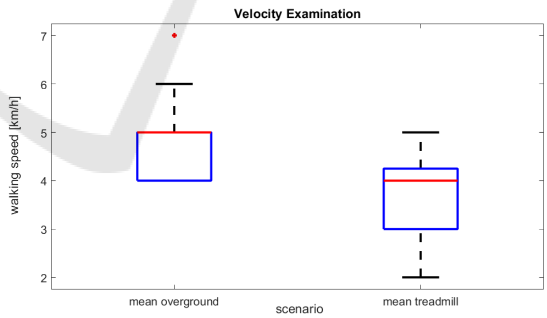


Figure 3: Boxplots of the walking speed during the two walking scenarios (overground and treadmill) with a higher median walking speed for the overground setting.

4 DISCUSSION AND CONCLUSION

The velocity examination shows that the motorization of the treadmill affects the perception of self selected comfortable walking speed. On average, the walking speed on the TM is reduced by approximate 1 km/h

Table 1: Parameters of the OG walking compared to the TM walking (TM1 and TM2) of the muscle M. gastrocnemius medialis (GM). * stands for p<0.01 and ** for p<0.05.

GM	Parameter	mean OG	mean TM	mean difference	mean quotient (%)
OG vs. TM1	Peak occurence (%)	38.00	37.30	-0.70	98.21
	peak height (mV)	4722.93	3963.36	-759.57*	83.92
	peak width (%)	23.18	26.33	3.15*	113.59
	integral (UA)	84305.29	79261.56	-5043.73**	94.02
OG vs. TM2	Peak occurence (%)	38.00	37.88	-0.12	99.63
	peak height (mV)	4722.93	4312.86	-410.07*	91.32
	peak width (%)	23.18	24.42	1.24	105.36
	integral (UA)	84305.29	81169.29	-3136.00**	96.28

Table 2: Parameters of the OG walking compared to the TM walking (TM1 and TM2) of the muscle M. gastrocnemius lateralis (GL). * stands for p<0.01.

GL	Parameter	mean OG	mean TM	mean difference	mean quotient (%)
OG vs. TM1	Peak occurence (%)	40.52	40.52	0.00	99.96
	peak height (mV)	3470.75	2621.18	-849.57*	75.52
	peak width (%)	20.14	29.36	9.22*	145.80
	integral (UA)	54551.43	54472.49	-78.93	99.86
OG vs. TM2	Peak occurence (%)	40.52	40.97	0.45	101.08
	peak height (mV)	3470.75	2763.14	-707.61*	79.61
	peak width (%)	20.14	25.29	5.16*	125.60
	integral (UA)	54551.43	52228.61	-2322.81	95.74

Table 3: Parameters of the OG walking compared to the TM walking (TM1 and TM2) of the muscle M. soleus (SO). * stands for p<0.01.

SO	Parameter	mean OG	mean TM	mean difference	mean quotient (%)
OG vs. TM1	Peak occurence (%)	41.61	41.56	-0.09	99.76
	peak height (mV)	2575.85	1773.51	-802.34*	68.85
	peak width (%)	20.22	30.00	9.78*	148.39
	integral (UA)	39982.37	38522.78	-1459.59	96.35
OG vs. TM2	Peak occurence (%)	41.61	41.74	0.13	100.32
	peak height (mV)	2575.85	1720.35	-855.50*	66.79
	peak width (%)	20.22	26.13	5.91*	129.25
	integral (UA)	39982.37	34550.92	-5431.45*	86.42

compared to the walking velocity in the OG setting. The literature shows similar results, but partly not in these dimensions. In walking scenario, Arsenault et al. (Arsenault et al., 1986) and Marsh et al. (Marsh et al., 2006) found a difference in speed of 0.3 km/h or 1.4 km/h, respectively. Oliveira et al. (Oliveira et al., 2016) and Kong et al. (Kong et al., 2012) investigated running scenarios and registered differences in the self-selected and comfortable running velocity of 0.4 km/h or 4.2 km/h.

Considering the muscle activation during walking, the results of our investigations confirm that there are differences between OG and TM walking. The considered hypothesis that the primary plantar flexor muscles are less activated during TM walking than in OG walking can be verified with the present results considering the parameter peak height. Referring the parameter peak occurence no difference in the temporal appearance of the maximum activation of the plantar flexor muscles could be found in the investigated sample. At the moment, the effect represented by the positive difference between the settings (OG vs. TM1, OG vs. TM2) of the parameter peak width resulting in a percentual quotient larger than 100 % cannot be interpreted. Compared to the OG walking the activation curve shows a broader but flatter course for the TM walking. That means that the muscle is earlier and longer activated during the gait cycle. The reason for that phenomenon is currently unknown.

The statements published by Oliveira et al. can only be partially confirmed (Oliveira et al., 2016). The authors found a higher activation of the SO and a lower activation of the GM and GL during OG walking. Compared to our approach Oliveira et al. (Oliveira

et al., 2016) examined the muscle activation while overground and treadmill running. In contrast, our findings show a higher activation for all primary plantar flexor muscles during OG walking.
The determined parameters of the muscle activation indicate that there is an effect of different, adjustable conditions (speed and inclination). Using the recommended inclination of 1.5 %, a little higher activation of the primary plantar flexor muscles is recognizable. With the exception of SO showing a decrease, an increase in muscle activation of 4 to 7 % was observed. However, the temporal occurrence of the maximum activation of the muscles is not influenced by these conditions.
In future, examinations are planned to find detailed information about the different conditions and their impact on the muscle activation in order to find recommendations for therapeutic interventions or training programs. For achieving the goal, these facts are important to know.
Furthermore, investigations with CP patiens should be conducted in order to find the impact of the conditions to the gait and the muscle activation of these patients. Depending on the CP-type the setting and the detection of gait initiation have to be changed.

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