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Muscle Contracture Emulating System for Studying Artificially Induced Pathological Gait in Intact Individuals

Andrej Olenšek[1], Zlatko Matjačić[1], and Tadej Bajd[2]
[1]Institute for Rehabilitation, Slovenia; [2]University of Ljubljana

When studying pathological gait it is important to correctly identify primary gait anomalies originating from damage to the central nervous and musculoskeletal system and separate them from compensatory changes of gait pattern, which is often challenging due to the lack of knowledge related to biomechanics of pathological gait. A mechanical system consisting of specially designed trousers, special shoe arrangement, and elastic ropes attached to selected locations on the trousers and shoes is proposed to allow emulation of muscle contractures of soleus (SOL) and gastrocnemius (GAS) muscles and both SOL-GAS. The main objective of this study was to evaluate and compare gait variability as recorded in normal gait and when being constrained with the proposed system. Six neurologically and orthopedically intact volunteers walked along a 7-m walkway while gait kinematics and kinetics were recorded using VICON motion analysis system and two AMTI forceplates. Statistical analysis of coefficient of variation of kinematics and kinetics as recorded in normal walking and during the most constrained SOL-GAS condition showed comparable gait variability. Inspection of resulting group averaged gait patterns revealed considerable resemblance to a selected clinical example of spastic diplegia, indicating that the proposed mechanical system potentially represents a novel method for studying emulated pathological gait arising from artificially induced muscle contractures in neurologically intact individuals.

Key Words: toe-walking, gait pattern, equinus

Gait anomalies rarely occur in isolation. Rather they are multiple and consist of primary anomalies which can be directly attributed to damage to the central nervous system or musculoskeletal system, and secondary anomalies that individuals develop to compensate for unwanted effects arising from primary anomalies. Establishing appropriate diagnosis and developing a proper treatment plan calls for separation

[1]Institute for Rehabilitation, Linhartova 51, SI-1000 Ljubljana, Slovenia; [2]Faculty of Electrical Engineering, University of Ljubljana, Trzaška c. 25, 1000 Ljubljana, Slovenia.

of primary from secondary anomalies, as only primary anomalies should be suppressed by appropriate therapeutic (Duncan, 1989; Tardieu, Lespargot, Tabary, & Bret 1988), pharmacological (Metaxiotis, Siebel, & Doederlein, 2002), orthotic (Carmick, 1995; Hanson & Jones, 1989), or surgical (Orendurff, Aiona, Dorociak, & Pierce, 2002) intervention. In most cases secondary anomalies will diminish after primary anomalies are properly treated. This task is often very challenging, mostly because of our limited knowledge on biomechanical phenomena accompanying pathological gait (Gage, 1993; Hanson & Jones, 1989).

When studying human gait, instrumented kinesiological assessment and analysis of joint kinematics, kinetics, and muscle EMG signals are indispensable. Combined with detailed biomechanical modeling and optimization techniques, we can gather valuable insight into functional roles of particular muscle groups during the gait cycle, which sheds light on the dynamic interplay of the neuromuscular system during walking (Zajac, Neptune, & Kautz, 2002, 2003). However, when studying pathological gait it is often impossible to predict potential compensatory mechanisms, which may alter the functional role of particular muscles, by means of biomechanical computer modeling and simulation. This is because in the model we would also need to include the control mechanisms of gait, which are unknown (Hogan, 1985).

Toe-walking represents a very common example of pathological gait (Gage, 1991; Kelly, Jenkinson, Stephens, & O'Brien, 1997; Policy, Torburn, Rinsky, & Rose, 2001; Winter, 1991). Toe-walking is a gait irregularity arising from various neuromuscular diseases; most frequently it is present in children with cerebral palsy. It is a result of prolonged and premature ankle plantarflexor activity and plantarflexor spasticity and/or plantarflexor contracture. Equinus gait pattern must be corrected, as such gait pattern reduces walking speed, decreases stride length, creates balance difficulties, and increases energy demands. In children with cerebral palsy, toe-walking can lead to bone deformities. Currently there are no sound biomechanical classifications of toe-walking gait to help the clinician determine the severity of a particular case. In practice the degree of equinus is often the key indicator for the planning of treatment.

Recently two studies investigated the kinematic, kinetic, and EMG characteristics of toe-walking, which was self-induced in the gait of neurologically and orthopedically intact individuals (Kerrigan, Oiley, Rogan, & Burke, 2000; Perry, Burnfield, Grongley, & Mulroy, 2003). Another distinctive approach to impose equinus gait in the healthy adult is presented in Goodman, Menown, West, et al. (2004), who used a special taping technique to constrain mobility in the ankle in order to impose an equinus constraint. However, since plantarflexors are constituted from monoarticular SOL muscle and biarticular GAS muscle, we can assume that spasticity or contracture of each muscle or both combined may have different biomechanical effects on the resulting gait pattern in the joints of both lower extremities. Thus, the approaches of Kerrigan et al. (2000), Perry et al. (2003), and Goodman et al. (2004) cannot control the extent to which soleus and gastrocnemius contractures contribute to toe-walking.

In this paper we present a novel mechanical system which is designed to ensure well-controlled conditions for repeatable emulation of artificially induced toe-walking gait in neurologically intact persons. The system enables emulation of soleus muscle contracture, gastrocnemius muscle contracture, or both contractures combined. The system was tested in 6 individuals for evaluation of gait pattern

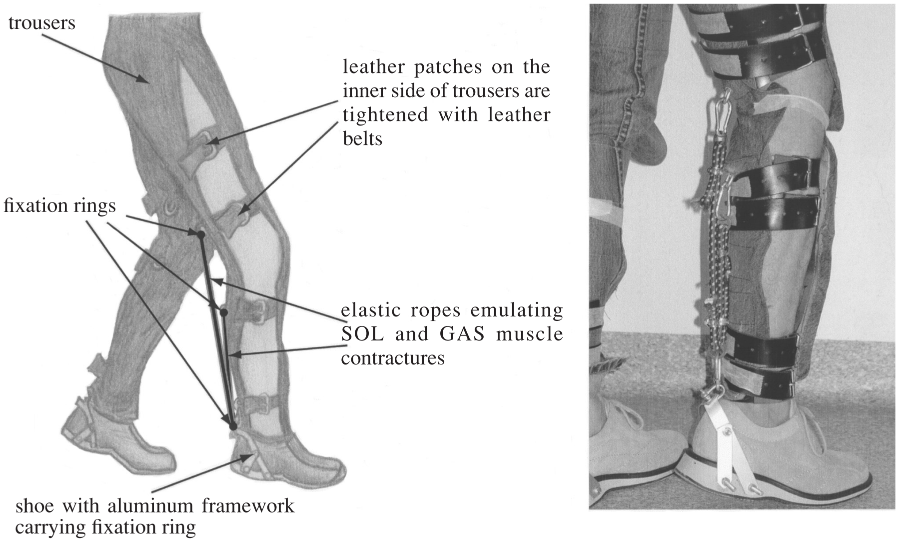


Figure 1 — Schematic and photograph of a participant during walking with emulation of SOL and GAS muscle contracture. The system consists of trousers with leather patches sewed on the inner side and two fixation rings corresponding to proximal ends of SOL and GAS muscles, shoes with aluminum framework carrying fixation ring corresponding to distal ends of SOL and GAS muscles, and elastic ropes, representing emulated muscle contractures.

variability, and resulting gait patterns were qualitatively compared to a selected clinical example of toe-walking in spastic diplegia.

Methods

Figure 1 shows a schematic drawing and a photograph of the actual mechanical system that resembles a kind of soft exoskeleton consisting of specially sewed trousers, special shoe arrangement, and elastic ropes attached at the proximal end to the designated locations on the trousers and at the distal end to the fixation frame at the heels of the shoes.

The trousers are made of durable material able to withstand mechanical loading without tearing apart. The primary mechanical loading on the trousers comes from the stretched elastic ropes, which tend to provoke relative movement of trousers on the leg. This movement is prevented by leather patches embracing the thigh and shank of the lower extremity. Altogether 4 leather patches are longitudinally and transversally sewed to the inner side of the left and right trouser legs. Fastening 4 leather belts on each leather patch keeps the whole arrangement firmly secured to the leg, preventing the trousers from moving vertically during walking. At the same time the hip, knee, and ankle joints remain uncovered and freely movable. The friction between leg and leather patches is enhanced by using rough surface leather patches. The trouser legs on the outer sides remain unstitched up to the pelvis level, providing enough space for fastening the belts.

Metal fixating rings are mounted directly on the trousers and leather patches at the approximate positions where particular muscles are attached to the bone. Iron nuts, tightening the fixating rings on both sides of the leather patches, were covered with soft leather tissue to ensure soft skin contact and firm attachment points for elastic ropes. Located beneath and posterior and above and posterior to the knee joint axis, the first and second fixating rings correspond to the proximal ends of SOL and GAS muscles, respectively. Distal ends of both muscles are attached to the heel arrangement of the shoe posterior to the ankle joint axis on the third fixating ring. Two aluminum bars are bent in the shape of the heel and mounted on shoes with iron bolts and nuts through the shoe heels. Carrying the third fixating ring, the first bar is on both sides of the shoe supported by the second bar, together forming triangles and thus preventing the frame from moving.

Muscle contracture is emulated with one or more elastic ropes connected in parallel with a particular muscle. When choosing appropriate length and stiffness of elastic ropes, we needed (a) to prevent the elastic rope from exceeding its elastic limits, which would induce unwanted perturbation in walking, and (b) to ensure that the arrangement imposes equinus gait. After a series of trial-and-error tests, three restrictive situations that meet these conditions were selected for repeatability analysis. SOL contracture refers to the experiment when three 16-cm long elastic ropes, each of 1115 N/m stiffness, were emulating SOL muscle contracture whereas GAS contracture designates an experiment when three 21-cm long elastic ropes, each of 850 N/m stiffness, were emulating GAS muscle contractures. Similarly, we further used the SOL-GAS contracture term when two pairs of elastic ropes were used for simultaneous emulation of SOL and GAS muscle contractures. The SOL pair was composed of two 16-cm long elastic ropes, each of 1115 N/m stiffness, while the GAS pair was composed of two 21-cm long elastic ropes, each of 850 N/m stiffness. When the elastic ropes remained unattached, the experimental condition was referred to as normal gait.

The main goal of experimental evaluation of the developed mechanical system was to investigate whether repeatable patterns of emulated walking can be achieved. In this respect, we compared normal walking, SOL contracture, GAS contracture, and SOL-GAS contracture in 6 neurologically and orthopedically intact volunteers who were equipped with the proposed system. Their data are listed in Table 1. A VICON motion analysis system (VICON 370, Oxford Metrics Ltd., Oxford, U.K.)

Table 1 Characteristics of Participants in the Study

Participant	Age (yrs)	Height (cm)	Weight (kg)
1	19	178	60
2	23	179	62
3	23	172	66
4	24	176	67.4
5	24	168	61.7
6	22	177	71
Mean ± *SD*	22.5 ± 1.87	175.0 ± 4.2	64.2 ± 4.2

and a 15-marker placement according to Vicon Clinical Manager protocol were used to capture 3-D motion of the lower limbs and pelvis. Ground reaction forces were recorded at a sampling frequency of 1,000 Hz with two AMTI force plates (AMTI OR-6-5-1000, Advanced Mechanical Technology Inc., Watertown, MA) that were positioned in the center of a 7-m walkway. Kinematic and kinetic data were processed with Vicon Clinical Manager software. During the experiments the participants were monitored to maintain walking speed of approximately 1 m/s. The protocol was approved by the Slovenian medical ethics committee and the participants signed a written consent.

At least 4 steps with the left foot (equipped with elastic ropes in the constrained situations) were recorded and averaged in each experimental condition (normal walking, SOL contracture, GAS contracture, and SOL-GAS contracture) to produce mean values and standard deviations of kinematic and kinetic trajectories in each participant. These standard deviations were averaged across the gait cycle for each trajectory separately to constitute a coefficient of variation, defined with Equation 1. CV was used as a measure of gait variability in a subsequent gait variability analysis where a two-tailed paired *t*-test of CV values for each kinematic and kinetic trajectory was performed separately on a group of 6 participants when walking normally and when SOL-GAS muscle contracture was emulated, as this experimental condition imposes the highest mechanical loading on the trousers. The level of statistical significance was set at $p < 0.05$.

$$CV = \frac{1}{N}\sum_{i=1}^{N}\sigma_i$$

CV = coefficient of variation; N = number of samples over the stride (50); σ_i = standard deviation of variable about an i-th sample.

Mean values of kinematic and kinetic trajectories of all 6 participants were further averaged to obtain group average values and standard deviations of kinematic and kinetic trajectories, which were presented graphically.

Results

Results of a two-tailed paired *t*-test between CVs in normal walking and SOL-GAS contracture for all joint angles, moments, and powers are listed in Table 2. Compared to normal walking, the biggest differences in the SOL-GAS experimental condition occur in ankle recordings; however, they do not indicate statistically significant increase of mean CV values. Likewise, we did not find statistically significant differences in gait variability in knee and hip recordings, where mean values of CV are very much alike and p values are well above the level of statistical significance. In general, the variability of gait was comparable between both experimental conditions.

Figure 2 shows group average and standard deviations of kinematic and kinetic recordings for 6 participants when walking normally and when SOL, GAS, and SOL-GAS contractures were emulated. We can observe similar plantar flexion during the initial contact and swing and plantar flexor moment profiles in all constrained situations, while more distinctive knee motion and knee moments can be observed for particular contracture emulation patterns. As opposed to nearly normal knee angle trajectory and reduced knee extensor moment in the stance phase when emulating

Table 2 Average Values (± *SD*) of CV in Normal Walking and SOL-GAS Muscle Contracture for 6 Participants Compared in Two-Tailed Paired *t*-Test

	Normal walk Mean ± *SD*	SOL-GAS contracture Mean ± *SD*	Paired *t*-test (*p* value)
Ankle angle (deg)	1.319 ± 0.281	2.050 ± 0.777	0.089
Ankle moment (Nm/kg)	0.078 ± 0.102	0.057 ± 0.013	0.010
Ankle power (W/kg)	0.158 ± 0.019	0.223 ± 0.063	0.053
Knee angle (deg)	1.734 ± 0.417	1.611 ± 0.618	0.711
Knee moment (Nm/kg)	0.075 ± 0.027	0.062 ± 0.016	0.372
Knee power (W/kg)	0.165 ± 0.029	0.125 ± 0.034	0.122
Hip angle (deg)	0.897 ± 0.176	0.951 ± 0.377	0.756
Hip moment (Nm/kg)	0.122 ± 0.032	0.106 ± 0.020	0.418
Hip power (W/kg)	0.159 ± 0.039	0.123 ± 0.026	0.157

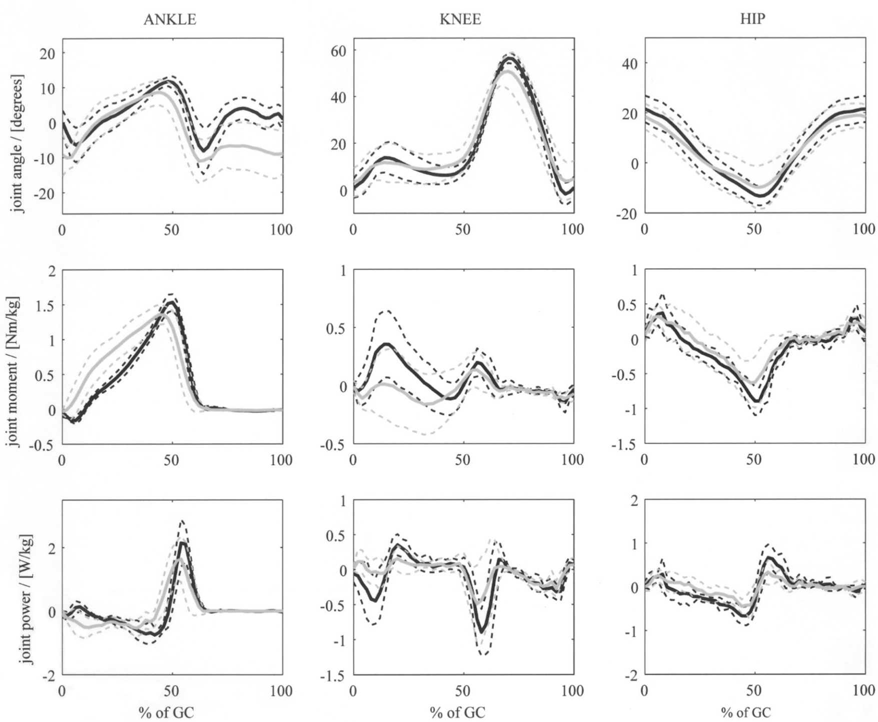
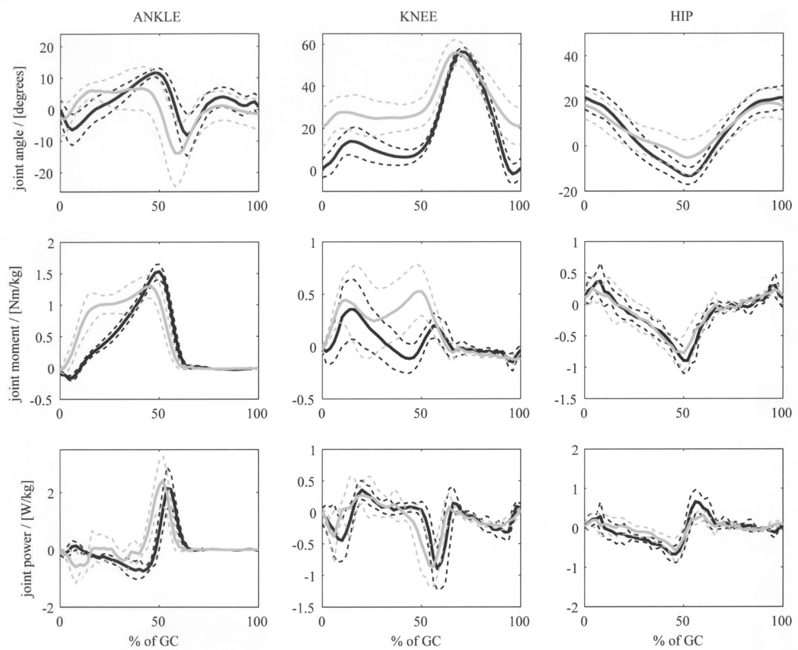
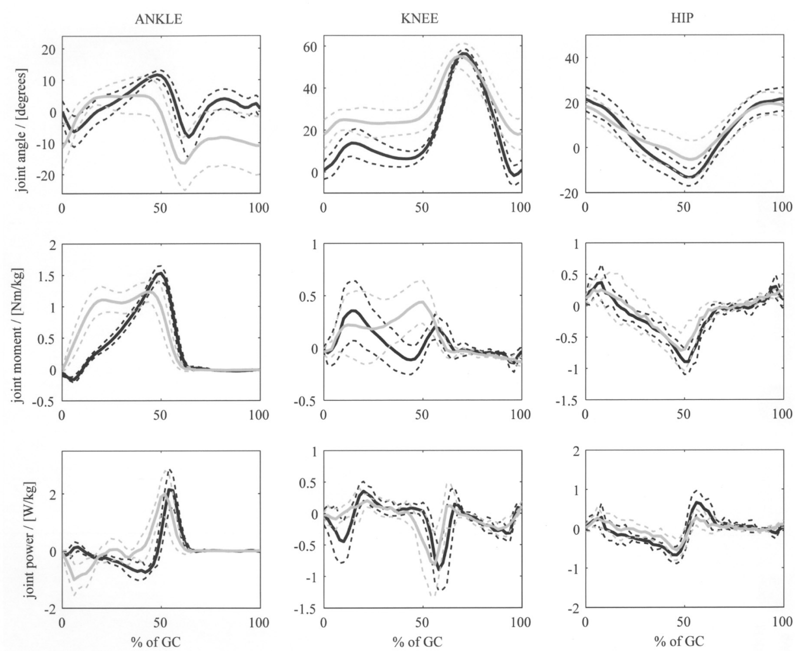


Figure 2a — Comparing normal gait with emulation of SOL muscle contracture. Black line = normal walking; grey line = emulating SOL contracture.

b)



c)



Figures 2b and 2c — Comparing normal gait with emulation of GAS muscle contracture (top) and SOL-GAS muscle contracture (bottom). Black line = normal walking. Grey line in 2b = emulating GAS contracture; in 2c = emulating SOL-GAS contracture.

SOL contracture, GAS contracture is characterized with increased knee flexion and knee extensor moment trajectories. Very similar knee motion and moment trajectories were recorded in the SOL-GAS experimental condition, where mostly a decrease in knee moment trajectory in midstance distinguishes this condition from the GAS contracture emulation pattern. The standard deviations of the trajectories in Figure 2 show comparable gait variability in all experimental conditions.

Discussion

We have developed a mechanical system enabling well-controlled imitation of SOL and GAS muscle contractures in neurologically and orthopaedically intact subjects. The system acts in a way to add mechanical stiffness to the peer muscle (for example, SOL elastic ropes to mechanical stiffness of soleus muscle) as well as to change a neutral position of lower extremity joints. These conditions can roughly approximate pathological states of increased muscle stiffness or reduced muscle length in static muscle contracture. However, the system does not account for phasic spastic activity that may accompany changes in muscle length and stiffness.

The results presented in Figure 2 demonstrate that the imposed contractures of SOL and GAS muscles affect ankle, knee, and hip kinematics and kinetics in a repeatable and distinctive way. By varying the stiffness of the elastic ropes and also by emulating various combinations of plantarflexor muscle contractures, we can investigate the biomechanical characteristics of different equinus constraints in the gait of a healthy adult in controlled conditions. Since the primary cause of altered gait pattern is known, we can identify secondary, compensatory changes. Acquired kinematic and kinetic patterns, having distinct characteristics, can then be qualitatively contrasted to a particular case of pathological gait in order to determine what could be the main cause for the observed gait pattern.

Results as recorded in three constrained situations were compared to a selected clinical case that was assessed in our laboratory. We present kinematic and kinetic patterns for left and right leg as recorded in a 10-year-old boy who was hospitalized in our institution and was diagnosed as having spastic diplegia (Figure 3). Pronounced plantar flexion in the swing phase and at the initial contact, increased ankle moment in midstance, and alternating periods of power absorption and generation in the stance phase followed by limited power generation at preswing show the typical pattern of a toe-walker. Compared to normal walking of our participants, we can also notice excessive knee flexion in the stance phase and excessive knee moment in the late stance phase. Additionally, left and right sides differ in the midstance knee extensor moment pattern where we notice a somewhat lower knee extensor moment of the left leg and a somewhat greater one of the right leg. Qualitative comparison indicates that ankle and knee trajectories of the left leg correspond more to the SOL-GAS pattern whereas ankle and knee trajectories of the right leg correspond more to the GAS pattern.

Comparing gait patterns of a patient and gait patterns as recorded when emulating muscle contractures shows differences in hip motion trajectories where all three restrictive situations are characterized with nearly normal hip motion, whereas excessive hip flexion marks the gait of a patient and is due to hip flexor contracture and accompanying lordosis. The above qualitative comparison indicates that studying emulated toe-walking in neurologically intact persons may be useful for interpreting clinical cases.

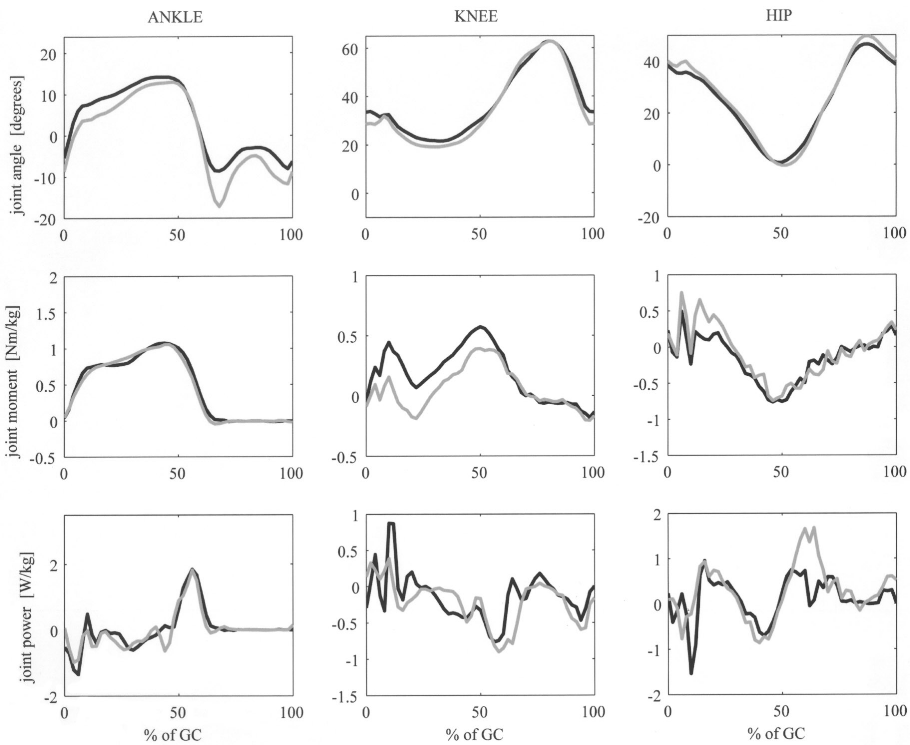


Figure 3 — Gait pattern as recorded in a 10-year-old boy who was diagnosed as having spastic diplegia. Black line = right; grey line = left.

The gait patterns under SOL contracture emulation can to some extent be related to "self-induced" toe-walking, as recorded in Kerrigan et al. (2000) and Perry et al. (2003), while GAS and SOL-GAS contracture gait patterns are considerably different from those in Kerrigan et al. and Perry et al. On the other hand, visual comparison of GAS or even more SOL-GAS contracture patterns reveals considerable similarity to patterns as recorded when using a special taping technique as described in Goodman et al. (2004). This indicates that the methods of Kerrigan et al. (2000), Perry et al. (2003), and Goodman et al. (2004) can only partially reveal the mechanisms of toe-walking where involvement of particular plantarflexor muscles distinctively determines kinematics and kinetics.

The main goal of the present work was to develop a mechanical system (see Figure 1) that would enable emulation of pathological gait patterns in neurologically and orthopedically intact individuals in a repeatable way. Therefore we evaluated gait variation in kinematic and kinetic gait patterns of 6 individuals as recorded during walking. The results show not only considerable resemblance between standard deviations of gait patterns as recorded in normal conditions and when emulating muscle contractures, but also provide no statistically significant indication on greater gait variability when analysis of coefficients of variation was undertaken. This suggests that the mechanical design of the system, providing a good grip between leather patches and leg skin and preventing the trousers from slipping, is a potential method for emulation of pathological gait patterns in a repeatable way.

The single disadvantage of the developed system is that the participants must be of similar height and weight due to the size of trousers and shoes. Also, a participant with a substantially greater capacity to generate power could overwhelm the strength of elastic ropes; therefore a direct comparison between participants would not be possible. For these reasons, persons of similar height, weight, and physical condition need to be chosen to participate in the experiments, making the results between participants directly comparable.

The developed system in its present form can be used only for emulation of SOL and GAS contractures; however, it can easily be expanded to allow emulation of contractures of other muscles of the lower extremity. The most interesting choices would be psoas, biceps femoris, and rectus femoris muscles. This expansion of system variety could easily be done by mounting mechanical rings at the appropriate anatomical sites on the leather patches of the trousers. A variety of combinations can be studied and compared to gait patterns recorded with single muscle contracture emulation. After a number of combinations have been extensively examined, we might be able to imitate conditions under a particular pathological state and distinguish between various disabling impairments, which could be helpful when identifying the source of impairment and deciding on the appropriate treatment.

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