

# Biomechanical characterization and clinical implications of artificially induced toe-walking: Differences between pure soleus, pure gastrocnemius and combination of soleus and gastrocnemius contractures

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## Abstract

The purpose of this study was to characterize biomechanically three different toe-walking gait patterns, artificially induced in six neurologically intact subjects and to compare them to selected cases of pathological toe-walking. The subjects, equipped with lightweight mechanical exoskeleton with elastic ropes attached to the left leg's heel on one end and on shank and thigh on the other end in a similar anatomical locations where soleus and gastrocnemius muscles attach to skeleton, walked at speed of approximately 1 m/s along the walkway under four experimental conditions: normal walking (NW), soleus contracture emulation (SOL), gastrocnemius contracture emulation (GAS) and emulation of both soleus and gastrocnemius contractures (SOLGAS). Reflective markers and force platform data were collected and ankle, knee and hip joint angles, moments and powers were calculated using inverse dynamic model for both legs. Characteristic peaks of averaged kinematic and kinetic patterns were compared among all four experimental conditions in one-way ANOVA. In the left leg SOL contracture mainly influenced the ankle angle trajectory, while GAS and SOLGAS contractures influenced the ankle and knee angle trajectories. GAS and SOLGAS contractures significantly increased ankle moment during midstance as compared to SOL contracture and NW. All three toe-walking experimental conditions exhibited significant power absorption in the ankle during loading response, which was absent in the NW condition, while during preswing significant decrease in power absorption as compared to NW was seen. In the knee joint SOL contracture diminished, GAS contracture increased while SOLGAS contracture approximately halved knee extensor moment during midstance as compared to NW. All three toe-walking experimental conditions decreased hip range of motion, hip flexor moment and power requirements during stance phase. Main difference in the right leg kinematic and kinetic patterns was seen in the knee moment trajectory, where significant increase in the knee extensor moment took place in terminal stance for GAS and SOLGAS experimental conditions as compared to SOL and NW. The kinetic trajectories under SOL and GAS experimental conditions were qualitatively compared to two selected clinical cases showing considerable similarity. This implies that distinct differences in kinetics between SOL, GAS and SOLGAS experimental conditions, as described in this paper, may be clinically relevant in determining the relative contribution of soleus and gastrocnemius muscles contractures to toe-walking in particular pathological gait.

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## 1. Introduction

Instrumented, quantitative gait analysis, including kinematic and kinetic measurements is gaining importance in diagnostics of pathological gait, in quantification of functional impairment as well as in

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planning appropriate treatment (Kerrigan, 1998). Especially, it is becoming an indispensable tool in the population of cerebral-palsied (CP) children (Gage, 1991, 1993). While technological facilities supporting instrumented gait analysis reached maturity over the last two decades, providing reliable tools that enable standardized and repeatable gait capturing, the main difficulty preventing full exploitation of recorded kinematic and kinetic recordings lays in the ability or inability of each team to correctly interpret these recordings (Davis, 1997). Often, the results of instrumented gait analysis display complex deviations from normal patterns, being a combination of altered central nervous system control as well as various degrees of muscle or joint contractures (static and dynamic). Therefore, separating an abnormal gait feature from adaptive compensatory strategy is the main and often very challenging task (Gitter and McAnelly, 1998).

When interpreting gait recordings we are lacking sound biomechanical characterization of resulting pathological gait patterns, which would enable us to delineate deviations that originate from altered muscle's biomechanical features and/or altered nervous control from compensatory adaptation. This task is particularly difficult because mechanical output of every single muscle in the multijointed biomechanical system affects the whole biomechanical structure due to mechanical coupling. We therefore need to further our knowledge of gait biomechanics on a level of particular muscle and its role during the gait cycle. Modeling and optimization seem to be very promising in shedding light into role of particular muscle in normal human gait (Neptune et al., 2001; Zajac et al., 2002, 2003; Anderson and Pandy, 2003). Once these muscle-based models are fully understood and developed we might be able to change various models' features to observe possible resulting gait alterations. However, to become fully credible these models would need to be also experimentally verified. Another possibility to study biomechanics and nervous control of altered gait is to instruct neurologically intact individuals to simulate particular pathological gait, i.e. toe-walking (Kerrigan et al., 2000; Perry et al., 2003). While this technique can provide valuable information to some extent, we must be cautious when interpreting the results as we cannot control the way such "self-restricted" walking alteration is accomplished in particular subject and in particular instant of gait cycle.

Pathological gait in CP population is classified solely according to kinematic gait patterns in the ankle, knee and hip joints (Winters et al., 1987; Rodda et al. 2004). These classifications are broad in definitions and aimed at practical clinical management. Very common example of pathological gait in CP population represents toe-walking, which is a result of either prolonged and premature ankle plantarflexors activity, plantarflexor spasticity and/or plantarflexor contractures (Gage,

1991). Since plantarflexors consist of monoarticular soleus muscle and biarticular gastrocnemius muscle we may expect different pathological gait patterns as a result of pathological state of each individual muscle or combination of both. Since it is not possible to clinically differentiate contractures of the gastrocnemius and the soleus by using Silverkiold test in a non-anesthetized patient (Gage, 1991), it is difficult for clinicians to locate the primary cause for foot equinus during walking, which may often be pathology of both soleus and gastrocnemius muscles and may be due to static and dynamic muscle function deformity. Furthermore, very similar kinematic recordings are obtained in instrumented gait analysis of toe-walking cases, especially when the primary problem (foot equinus) is compounded with other milder pathological changes at more proximal muscle groups, rendering the classifications based on kinematics useless for determining the degree of involvement of uniarticular and biarticular muscles of triceps surae group, which is important to select appropriate treatment.

Recently, we have proposed a novel method to artificially emulate pathological state of a selected leg muscle in neurologically intact individuals, by adding in parallel to a selected muscle an elastic rope having a mechanical stiffness that causes alteration in the selected joint's mobility and imposes biomechanical state that resembles muscle contracture (Olenšek et al., 2003). The rationale behind this approach is to selectively and in repeatable way induce a particular "impairment" of the biomechanical system and to observe the changed kinematic and kinetic patterns in all joints of the lower extremities. Our hypothesis is that different cases of alterations of soleus and gastrocnemius muscles' stiffness will result in distinct changes of kinetic gait patterns of artificially induced toe-walking that will resemble recorded kinetic patterns in selected CP cases.

The objective of this paper was to experimentally investigate the above hypothesis and to determine differences in kinematic and kinetic gait patterns in joints of both lower extremities in a group of neurologically and orthopedically intact individuals. Differences originated from artificially induced increase in stiffness of (i) soleus muscle, (ii) gastrocnemius muscle and (iii) combination of soleus and gastrocnemius muscles that forced the tested subjects into toe-walking. We further compared obtained kinetic patterns to selected CP cases from the literature in order to establish implications for clinical practice.

## 2. Methods

### 2.1. Subjects

Six male volunteers with no known neurologic or orthopedic disorders (age  $22.5 \pm 1.9$  years, height

175±4.2 cm, weight 64.2±4.2 kg) participated in the study. The experimental protocol was approved by the local ethics committee and the subjects signed informed consent forms.

## 2.2. Muscle contracture emulation system

Fig. 1a shows schematics of the mechanical system that was used to artificially emulate contractures of soleus and gastrocnemius muscles. The system consists of specially sewed trousers with leather patches with mounted metal nuts, shoes with special heel arrangement with mounted metal nut and series of elastic ropes of two different stiffnesses and lengths. Metal nuts on the trousers were placed at approximate locations where soleus and gastrocnemius attach to respective bones. Elastic ropes are attached at the proximal ends to the respective metal nuts on the trousers and at distal end on the nut mounted on the shoe heel arrangement. Fig. 1b shows photograph of the actual system. Particular muscle contracture can be emulated with one, two or three elastic ropes attached in parallel. Length and stiffness of elastic ropes were selected after careful experimentation where we aimed to achieve gradual increase of emulated pathological state in such a way that in conditions with three attached ropes the subjects were forced to toe-walk while simultaneously ensuring elastic behavior of artificial muscles. Elastic ropes emulating the soleus contracture were 16 cm long exhibiting 1115 N/m stiffness, while the ropes emulating the gastrocnemius contracture were 21 cm long exhibiting 850 Nm/m. A detailed description on the muscle contraction emulation system (MCES) is given in Olenšek et al., 2003.

## 2.3. Experimental conditions

Subjects walked across a 10 m-gait laboratory walkway under several experimental conditions. Within normal walk (NW) condition the subjects wore MCES without any elastic ropes attached. Within the experimental condition where the soleus muscle contracture was emulated (SOL) three elastic ropes attached to the trousers and the shoe arrangement on the left leg were applied. Within the experimental condition where the gastrocnemius muscle contraction was emulated (GAS) three elastic ropes attached to the trousers and the shoe arrangement on the left leg were applied. Within the experimental condition where contracture of both soleus and gastrocnemius muscles contractures were emulated simultaneously (SOLGAS) two ropes emulating soleus and two ropes emulating gastrocnemius contracture were applied. The right leg remained unconstrained in all experimental conditions.

A VICON motion capture and analysis system (VICON 370, Oxford Metrics Ltd., Oxford, UK) was

used to capture three-dimensional motion of lower limbs and pelvis. The system included six couple-charged cameras with strobed infrared light-emitting diodes and reflective markers attached to the subjects' skin over designated landmarks according to the specifications using standardized protocols provided by manufacturer of the system. Motion data were sampled at 50 Hz sampling rate. Two AMTI force plates (AMTI OR-6-5-1000, Advanced Mechanical Technology Inc., Watertown, MA) that were positioned in the center of a walkway were used for recording ground reaction forces. Force data were sampled at 1000 Hz sampling rate. During experiment the subjects were monitored to maintain walking speed of approximately 1 m/s. Using a simple stop watch, trials were discarded if the time to overcome the distance of 7 m differed more than one-half of a second from expected time of 7 s. Within each of the experimental conditions several walking trials were undertaken. Within each trial only one leg hit one of the force platforms. At least four clear steps of each leg were captured for analysis. Before capturing movement the subjects practiced walking for several minutes for each experimental condition. Between experimental conditions the subjects rested for 10 min.

## 2.4. Data analysis

Gait velocity, stride length and cadence data were extracted for each experimental condition. For each subject averaged values from four trials per each leg captured under each experimental condition were calculated and used in subsequent averaging of the data for the whole group separately for each experimental condition.

Sagittal ankle, knee and hip trajectories, joint moments and powers were calculated for each experimental condition using full-inverse dynamic model software provided by the manufacturer of the system. Joint moments and powers were normalized for body weight and reported in Nm/kg and W/kg, respectively. For each subject the averaged values from four trials per each leg captured under each experimental condition were calculated and used in subsequent averaging and statistical analysis of the data for the whole group separately for each experimental condition. Graphs displaying joint's angles, moments and powers for all experimental conditions were plotted together in order to enable inspection of qualitative differences and for qualitative interpretation. Gait cycle terminology as introduced by Perry (Perry, 1992) was adopted to define instants of characteristic peak values of kinematic and kinetic trajectories in the gait cycle, which were selected similarly to that in Kerrigan et al., 2000.

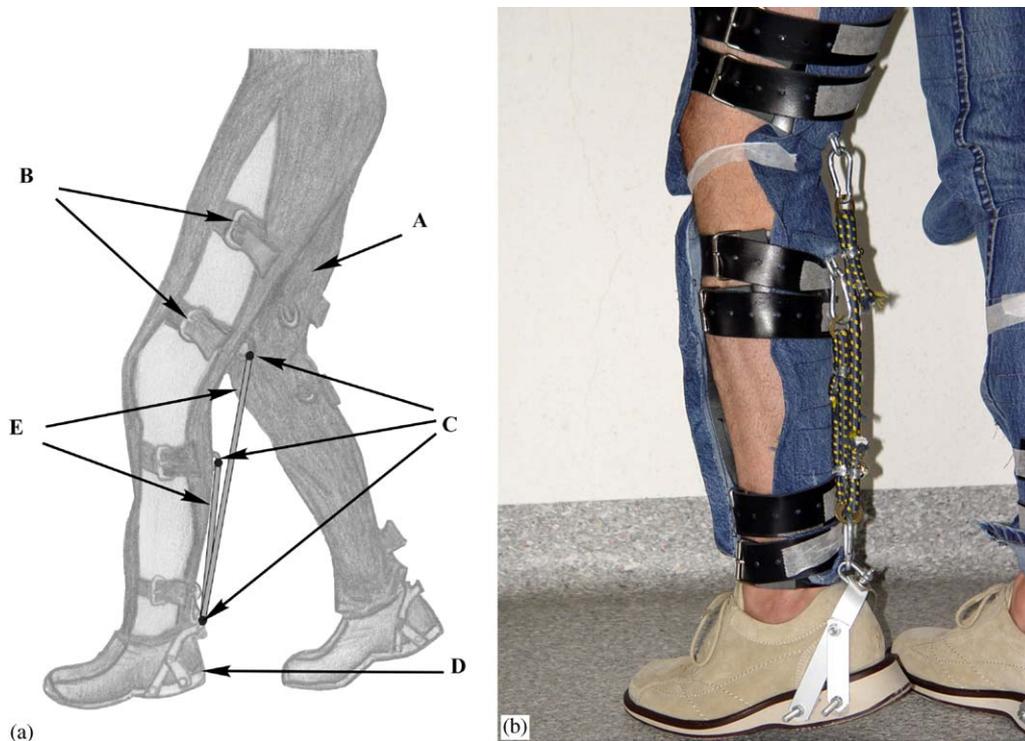


Fig. 1. (a) Schematic presentation of a walking subject, wearing muscle contracture emulation system with two elastic ropes, one emulating soleus muscle contracture and the other gastrocnemius muscle contracture. The system consists of: A—trousers made of durable material, B—leather patches on the inner side of trousers, C—fixation rings, D—shoe with aluminum framework, E—elastic ropes. (b) Photograph of the actual system.

## 2.5. Statistics

Statistical analysis was performed for each characteristic peak of the stance subphase (0%–10% loading response, 10%–30% midstance, 30%–50% terminal stance and 50%–60% preswing) in the joint trajectories, moments and powers obtained under the experimental conditions NW, SOL, GAS and SOLGAS, i.e. between NW and three different toe-walking gait patterns. Within each condition, each subject's average of four trials were used. Within each of the stance subphases one-way ANOVA was performed on either maximal or minimal values of each subject's averaged data with factor being one of the tested experimental conditions. Bonferroni adjusted post-hoc pair-wise comparisons were made when a main effect or interaction was detected.  $P < 0.05$  was regarded as statistically significant. All values are presented as mean and standard error of the mean value. Similarly data on gait velocities, stride lengths and cadences were statistically examined in one-way ANOVA.

## 3. Results

### 3.1. Temporal gait characteristics

Gait velocities, stride lengths and cadences for both legs did not differ significantly between different

experimental conditions. The data are gathered in Table 1.

### 3.2. Kinematics and kinetics

#### 3.2.1. Left leg

Fig. 2 shows averaged kinematic and kinetic trajectories across the subjects ( $N = 6$ ) for the left leg and for all experimental conditions.

Ankle angle trajectories differ throughout the whole gait cycle. During loading response, the foot is in pronounced plantarflexion for experimental conditions SOL and SOLGAS while for the experimental condition GAS the extent of plantarflexion is lower compared to NW. These differences are statistically significant (Table 2). During midstance the shape of trajectory under SOL experimental condition is similar to NW, while pronounced dorsiflexion characterizes experimental conditions GAS and SOLGAS. During terminal stance a noticeable and gradual decrease in achieved dorsiflexion characterizes all three toe-walking experimental conditions as compared to NW. Similarly in the preswing and swing phases pronounced plantarflexion is observed. These differences were not statistically significant.

Ankle moment trajectories show statistically significant lack of dorsiflexion moment during loading response for SOL, GAS and SOLGAS experimental

Table 1  
Temporal gait characteristics for all four experimental conditions ( $N = 6$ )

|                             | NW            | SOL          | GAS           | SOLGAS        | <i>P</i> value ANOVA |
|-----------------------------|---------------|--------------|---------------|---------------|----------------------|
| Gait velocity (m/s)         | 1.06 (0.02)   | 1.02 (0.05)  | 1.02 (0.03)   | 1.03 (0.04)   | 0.178                |
| Stride length left leg (m)  | 1.26 (0.07)   | 1.2 (0.09)   | 1.2 (0.07)    | 1.2 (0.07)    | 0.384                |
| Cadence left leg (1/s)      | 100.67 (3.56) | 99.46 (5.44) | 102.8 (7.8)   | 103.96 (8.78) | 0.654                |
| Stride length right leg (m) | 1.28 (0.06)   | 1.23 (0.06)  | 1.19 (0.08)   | 1.2 (0.07)    | 0.116                |
| Cadence right leg (1/s)     | 99.53 (3.01)  | 99.53 (6.32) | 102.78 (7.54) | 103.3 (7.92)  | 0.629                |

Given are mean values and standard errors.

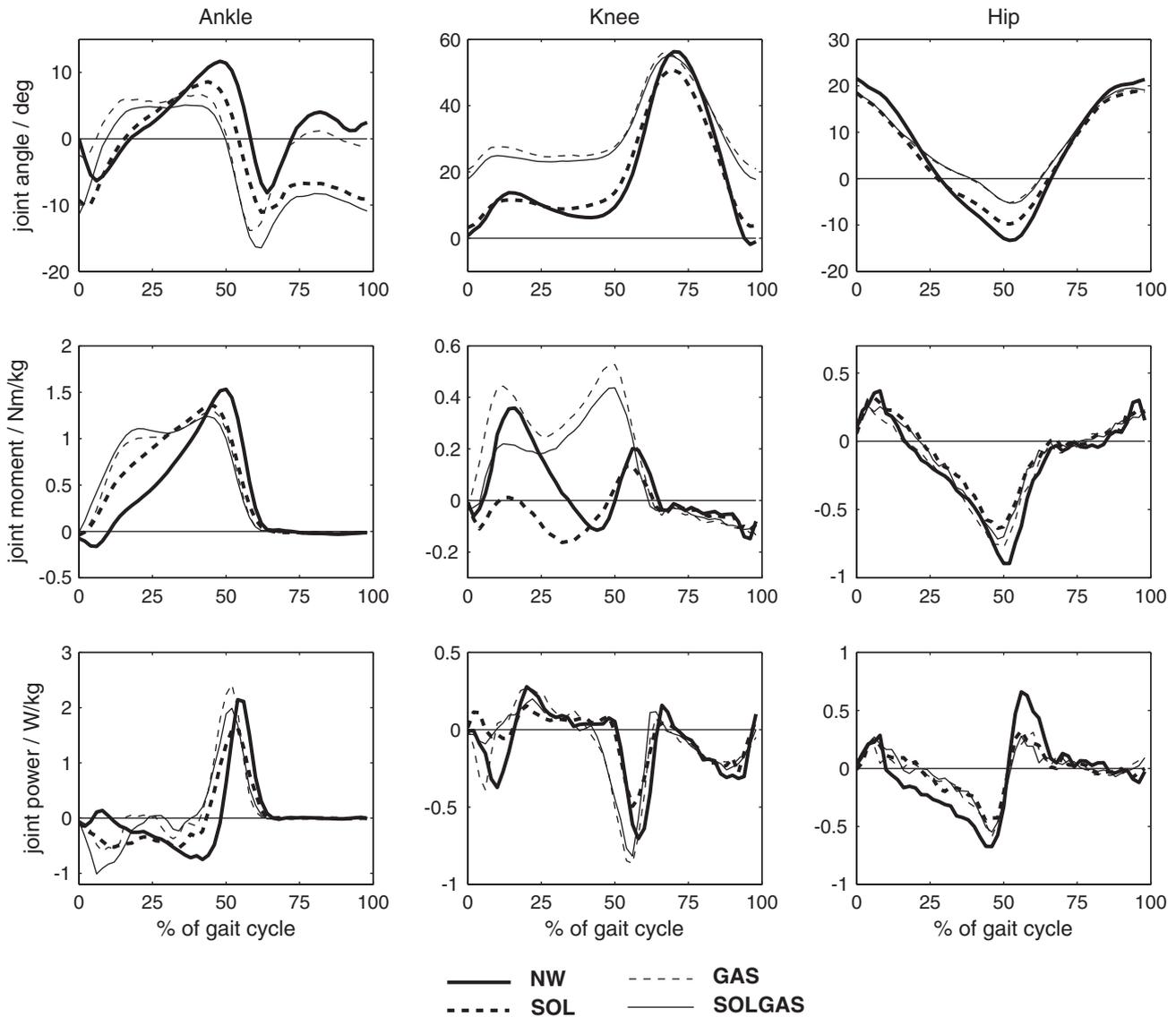


Fig. 2. Averaged kinematic and kinetic gait patterns captured for the left leg and for all four experimental conditions.

conditions as compared to NW (Table 2). Statistically significant higher values of plantarflexion moment occur during midstance with larger increase for GAS and SOLGAS as compared to SOL. During preswing statistically significant reduction in plantarflexion mo-

ment can be observed for all toe-walking experimental conditions as compared to NW.

Ankle power trajectories show statistically significant increase in power absorption during loading response, similar for SOL and GAS and higher for SOLGAS

Table 2  
Peak biomechanical variables for all four experimental conditions ( $N = 6$ )

|   | NW           | SOL          | GAS          | SOLGAS       | P value | ANOVA | Post-hoc main interactions (P value)   |
|---|--------------|--------------|--------------|--------------|---------|-------|--|
| <i>Left leg</i>                                     |              |              |              |              |         |       |  |
| Loading response, ankle angle (degrees)             | 0.67 (4.88)  | -5.21 (4.56) | 3.38 (5.09)  | -4.63 (7.03) | 0.035*  |       | —  |
| Midstance, knee flexion angle (degrees)             | 14.14 (6.44) | 12.11 (7.98) | 28.21 (8.62) | 25.56 (5.87) | 0.002*  |       | NW-GAS (0.02*) SOL-GAS (0.007*)<br>SOL-SOLGAS (0.028*)                         |
| Terminal stance, knee flexion angle (degrees)       | 5.53 (4.07)  | 8.37 (6.23)  | 24.15 (6.55) | 22.63 (5.6)  | 0.0001* |       | NW-GAS (0.0001*) NW-SOLGAS<br>(0.0001*) SOL-GAS (0.01*) SOL-<br>SOLGAS (0.02*) |
| Loading response, ankle dorsiflexion moment (Nm/kg) | -0.17 (0.04) | -0.06 (0.06) | -0.06 (0.04) | -0.01 (0.03) | 0.0001* |       | NW-SOL (0.007*) NW-GAS (0.003*)<br>NW-SOLGAS (0.0001*)                         |
| Mistance, ankle plantarflexion moment (Nm/kg)       | 0.63 (0.09)  | 1.03 (0.2)   | 1.16 (0.1)   | 1.16 (0.13)  | 0.0001* |       | NW-SOL (0.01*) NW-GAS (0.001*)<br>NW-SOLGAS (0.0001*)                          |
| Pre-swing, ankle plantarflexion moment (Nm/kg)      | 1.53 (0.11)  | 1.16 (0.24)  | 1.09 (0.25)  | 0.99 (0.32)  | 0.007*  |       | NW-GAS (0.034*) NW-SOLGAS<br>(0.007*)  |
| Loading response, knee flexion moment (Nm/kg)       | 0.27 (0.22)  | 0.06 (0.17)  | 0.44 (0.19)  | 0.23 (0.19)  | 0.028*  |       | SOL-GAS (0.02*)  |
| Midstance, knee extension moment (Nm/kg)            | 0.37 (0.28)  | 0.04 (0.28)  | 0.52 (0.33)  | 0.33 (0.3)   | 0.076   |       | —  |
| Terminal stance, knee moment (Nm/kg)                | -0.13 (0.14) | -0.17 (0.25) | 0.26 (0.28)  | 0.2 (0.25)   | 0.008*  |       | SOL-GAS (0.029*)   |
| Pre-swing, knee extension moment (Nm/kg)            | 0.21 (0.11)  | 0.15 (0.14)  | 0.54 (0.23)  | 0.44 (0.2)   | 0.004*  |       | NW-GAS (0.029*) SOL-GAS<br>(0.008*)  |
| Loading response, ankle power absorption (W/kg)     | -0.18 (0.1)  | -0.51 (0.35) | -0.67 (0.52) | -1.12 (0.42) | 0.004*  |       | NW-SOLGAS (0.003*)   |
| Terminal stance, ankle power absorption (W/kg)      | -0.85 (0.2)  | -0.62 (0.24) | -0.51 (0.27) | -0.34 (0.2)  | 0.009*  |       | NW-SOLGAS (0.007*)   |
| Loading response, knee power absorption (W/kg)      | -0.44 (0.35) | -0.1 (0.14)  | -0.45 (0.36) | -0.17 (0.1)  | 0.068   |       | —  |
| Pre-swing, hip power generation (W/kg)              | 0.72 (0.34)  | 0.37 (0.22)  | 0.32 (0.13)  | 0.33 (0.21)  | 0.025*  |       | —  |
| <i>Right leg</i>                                    |              |              |              |              |         |       |  |
| Terminal stance, knee moment (Nm/kg)                | -0.15 (0.08) | -0.16 (0.11) | 0.04 (0.16)  | 0.01 (0.15)  | 0.032*  |       | —  |

Given are mean values and standard errors.

\*  $p < 0.05$ .

while during midstance trajectories for SOL and NW are similar and show power absorption while trajectories for GAS and SOLGAS display almost isometric behavior. During terminal stance a marked power absorption takes place for NW while in all toe-walking experimental conditions the power absorption is smaller and the terminal stance phase is concluded earlier as compared to NW. Differences during terminal stance phase were statistically significant (Table 2). During the preswing phase lower values of power generation burst can be observed for SOL and SOLGAS while for the GAS a higher peak is noted as compared to NW.

The knee angle trajectories show considerable similarity between NW and SOL experimental conditions on one hand and GAS and SOLGAS experimental conditions on the other hand. During loading response, midstance and terminal stance the NW and SOL are substantially similar and differ significantly from the trajectories GAS and SOLGAS that show pronounced and statistically significant shift toward more flexion.

The knee moment trajectories display very different courses of trajectories among all experimental conditions. During loading response a characteristic initial burst of flexion moment can be seen in NW. This burst is even more pronounced in SOL and significantly attenuated in GAS and SOLGAS experimental conditions. In the beginning of midstance where normally knee extension moment reaches its peak value (NW) substantial differences can be observed. In the SOL trajectory we can see complete absence of extension moment, while even more pronounced extension moment is observed for GAS condition as compared to NW. For the SOLGAS condition we can see a combined effect of both individual muscle contracture emulations (SOL and GAS). The extension moment lies somewhere in between the trajectories of SOL and GAS conditions. While these differences are not statistically significant, very low  $p$  value (0.076, Table 2) suggests substantial difference. Indeed the same pattern is observed when inspecting individual graphs for all six tested subjects. Terminal stance in NW is characterized by a flexion moment, which is even more pronounced for SOL condition. Trajectories for GAS and SOLGAS experimental conditions show completely opposite characteristics where marked extension moments are present. There is a statistically significant difference among the experimental conditions in terminal stance (Table 2). Similar characteristics are valid also for the preswing phase, where trajectories for NW and SOL show similar amplitudes (slightly smaller moment for SOL), while the trajectories for GAS and SOLGAS display significantly higher extension moments.

The knee power trajectories generally differ between experimental conditions. While a burst of characteristic power absorption during loading response can be noticed for NW and GAS, much smaller power

absorption is present for SOLGAS, while a small burst of power generation can be seen for SOL condition ( $p = 0.068$ , Table 2). During midstance similar bursts of power generation are present for NW and GAS conditions, while the same bursts are attenuated in SOL and SOLGAS trajectories. During preswing power absorption bursts are higher for GAS and SOLGAS conditions and smaller for SOL condition as compared to NW.

The shape of hip angle trajectories is similar throughout the whole gait cycle for all experimental conditions. Noticeable decrease of hip flexion for SOL, GAS and SOLGAS conditions is seen as compared to NW during loading response. Also, all toe-walking conditions show decreased hip extension during preswing phase.

The hip moment trajectories are similar throughout the whole gait cycle with the exception of the preswing period where a decrease in flexion moment can be seen for the toe-walking experimental conditions as compared to the normative trajectory.

The hip power trajectories show similar shape throughout the whole gait cycle. Smaller power absorption is present during midstance and terminal stance phases among all three toe-walking experimental conditions, while there is a statistically significant difference between power generation bursts during preswing phase, where all three toe-walking conditions exhibit for almost 100% reduction in the peak amplitude as compared to the normative trajectory (NW).

### 3.2.2. Right leg

Fig. 3 shows averaged kinematic and kinetic trajectories across the subjects ( $N = 6$ ) for the right leg and for all experimental conditions.

Ankle angle, moment and power trajectories show substantial similarity between all experimental conditions. Slightly higher dorsiflexion is observed for SOL, GAS and SOLGAS conditions as compared to NW. More noticeable differences among the experimental conditions can be observed in the knee angle, moment and power trajectories. Higher knee flexion during the terminal stance phase is noticed for GAS and SOLGAS conditions as compared to SOL and NW conditions. The knee moment trajectories show increased flexion moment during loading response for all toe-walking conditions as compared to NW. During midstance the extension moments slightly differ depending on the experimental conditions. Statistically significant differences occur during terminal stance where for NW and SOL conditions we can observe expected flexion moment, while for GAS and SOLGAS conditions extension moments are seen. In the preswing there is a noticeably smaller extension moment for SOL condition as compared to the other three conditions. The knee power trajectories are similar for all experimental

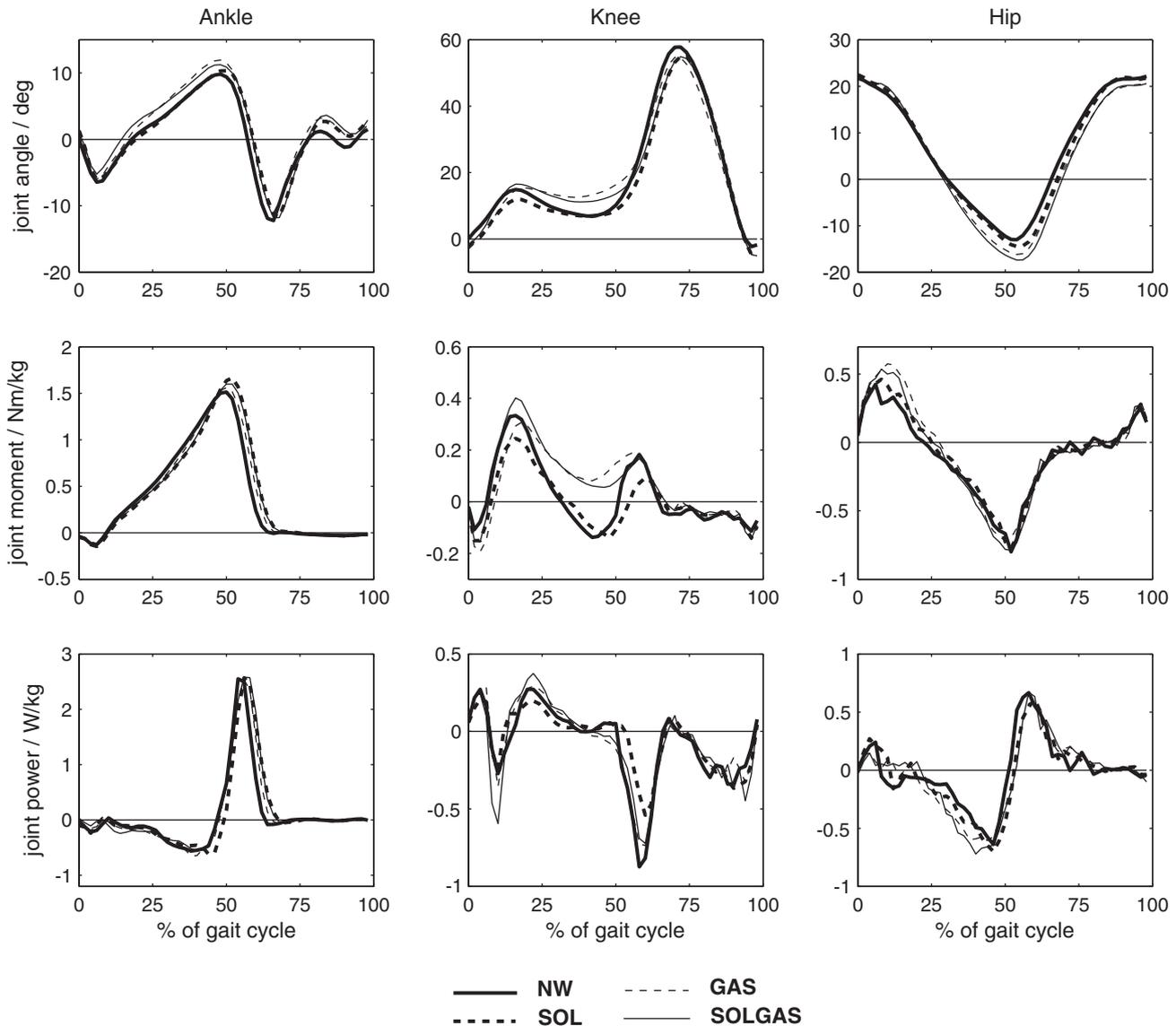


Fig. 3. Averaged kinematic and kinetic gait patterns captured for the right leg and for all four experimental conditions.

conditions with the exception of the preswing where a smaller power absorption is noticed for SOL as compared to the other three conditions. The shape of hip angle, moment and power trajectories is substantially similar in all experimental conditions. Increased hip extension can be noticed during the preswing phase for GAS and SOLGAS conditions as compared to NW and SOL conditions.

### 3.3. Biomechanical characterization and relation to selected clinical cases

#### 3.3.1. Left leg

In the case of pure soleus muscle contracture (SOL) the ankle angle trajectory is predominantly altered, while the knee and hip angle trajectories are comparable

to normative data. In comparison to normative data premature ankle plantarflexion moment occurred, while there was a considerable decrease in the knee extension moment during stance phase. Compared to normative data the whole stance phase was dominated by power absorption in the ankle, while normally present power absorption during loading response in the knee was absent. Also power generation in the hip during preswing was almost halved. Very similar kinetic recordings as those presented for SOL experimental condition are reported in Winter (1991, p. 106–107) under Case study #4—cerebral palsy hemiplegia. The knee moment trajectory shows net flexor moment very close to zero throughout the whole stance, while characteristic increase of ankle moment is present in the midstance. Winter explained this pattern by hyper-

active plantarflexors and according to our data this was caused primarily due to soleus muscle contracture.

Very different kinematic and kinetic patterns resulted in case of pure gastrocnemius muscle contracture (GAS). The ankle and knee angle trajectories are altered. Ankle dorsiflexion occurs earlier in the stance phase as compared to SOL condition while the knee angle is shifted into more flexed position throughout the stance phase. The hip angle trajectory shows reduced extension in the preswing phase. Ankle plantarflexion moment in the stance phase rose faster and was higher as compared to SOL condition, while the knee extension moment increased faster and was higher as in NW condition throughout the whole stance phase. The power absorption in the ankle during loading response was similar to SOL condition, however, it was diminished until the end of stance phase as compared to SOL condition. The knee power trajectory was similar to NW condition, while the hip power trajectories were similar to NW and SOL conditions. Clinical example showing similar ankle joint moment and ankle power trajectories are reported in Gage (1991, p. 145) characterized in double-teeth moment profile in the whole stance phase and strong power absorption in the midstance. Gage attributed observed kinetics to gastrocnemius dynamic contracture and performed Baker-type lengthening, which postoperatively resulted in near normal ankle joint kinematics and kinetics.

In the case of a combined soleus and gastrocnemius contracture (SOLGAS) we can observe combined effects of both pure contracture cases (SOL and GAS). The ankle angle trajectory is approximately a summation of SOL and GAS trajectories. The knee angle trajectory is approximately the difference of GAS and SOL trajectories. Hip angle trajectory is similar to GAS trajectory. In the ankle moment trajectory the effects of SOL and GAS contracture are synergetic while the opposite is the case for the knee moment trajectory where the SOL contracture acts to counterbalance the effect of GAS contracture, especially, during the midstance phase and to some extent also in the terminal stance and preswing phase. The hip moment trajectory is similar for all three toe-walking patterns. The power absorption in the ankle during loading response is enhanced by both SOL and GAS contractures, while in the rest of the stance phase GAS contracture acts to diminish power absorption effect of SOL contracture. The power absorption in the knee during loading response is diminished as SOL, and GAS contractures act to counterbalance the effects of each other. In the preswing the power absorption due to GAS contracture dominates. The hip power trajectory is similar to both SOL and GAS trajectories.

### 3.3.2. Right leg

Major differences observed in the joints of the right leg are in the knee joint, primarily as compensatory

adaptation to changed posture of the left leg during gait cycle. During the midstance and terminal stance phases the knee remains more flexed to match the length of the left leg, thereby minimizing pelvis and trunk vertical fluctuations. Consequently the ankle also goes into more dorsiflexion while the hip undergoes larger extension. With GAS and SOLGAS experimental conditions where these adaptations are more pronounced increased knee extension moment is needed during midstance and terminal stance phases.

## 4. Discussion

The objective of this study was to investigate biomechanical differences between three artificially induced toe-walking gait patterns, where (i) only soleus muscle contracture, (ii) only gastrocnemius muscle contracture and (iii) combination of soleus and gastrocnemius muscle contractures were emulated in neurologically and orthopedically intact individuals. Our hypothesis was that the kinetics of the lower extremities' joints would distinctively differ depending on the cause of equinus gait. The results of our study clearly show characteristic differences in gait patterns for the three possible causes of foot equinus, which may be used in determining the involvement of each muscle in toe-walking in particular patient when the problem originates primarily because of the dynamic or static contracture of plantarflexors. Findings of the present study can help clinicians to more reliably determine the degree of involvement of each muscle of triceps surae group in foot equinus, thereby facilitating correct decisions regarding treatment.

### 4.1. Biomechanical characterization

Presented biomechanical characterization of the reported kinematics and kinetics under the three emulated toe-walking gait patterns follows directly from the biomechanical consequences of particular emulated contractures. The SOL contracture directly influences the ankle joint and forces it into plantarflexion. Since the soleus muscle during NW dynamically induces acceleration in the knee that acts to extend the knee during the stance phase (Neptune et al., 2001), the SOL contracture reduces (or completely diminishes) the otherwise needed activity of knee extensors. The GAS contracture, however, directly influences the ankle and the knee, by forcing the ankle into plantarflexion and knee into flexion. Since the gastrocnemius muscle during NW dynamically induces acceleration in the knee that acts to flex the knee during the stance phase (Neptune et al., 2001), the GAS contracture increases the need for knee extensors output due to altered posture of the knee (ground reaction force passing behind the knee joint)

and also dynamically. Changes seen in the hip are primarily adaptation to the changed posture at the ankle and the knee which were adopted in order to maintain stride length. Therefore the changes observed in the hip angle, moment and power trajectories are all considered as compensations.

#### 4.2. Clinical implications

There are different opinions among clinicians as to what is the most common cause of equinus. Gage (1991) finds dynamic contracture of gastrocnemius as the most common ankle abnormality while Decq et al. (1998) state that in as much as 75% of all cases spasticity of soleus muscle is responsible for equinus foot. Clearly, such a difference in opinions will result also in different treatment approaches such as Botulinum toxin pharmacological injections in soleus and/or gastrocnemius muscles (Metaxiotis et al., 2002) or various surgical interventions aimed at triceps surae muscle group such as Achilles tendon lengthening (Orendurff et al., 2002) or gastrocnemius recession (Wren et al., 2004), producing very different biomechanical consequences for gait of particular patient. It is therefore important to objectively estimate the relative contributions of soleus and gastrocnemius muscles to equinus from the clinical gait analysis data in order to derive appropriate treatment plan in each particular case.

The selected clinical examples show substantial similarity to the data presented in this paper. However, the dominating pathological state of plantarflexors causing equinus can be accompanied with other milder pathological changes at more proximal muscle groups that may to some extent alter the kinetics and particularly kinematics of the ankle and the knee in each particular clinical case. On a contrary the data obtained under SOL, GAS and SOLGAS experimental conditions show “ideal” changes to kinematics and kinetics of particular emulated toe-walking gait patterns. Therefore, when relating the data from our study with the data from particular patient, this should be done qualitatively, searching for the distinct features in kinetic trajectories that may indicate the primary cause for toe-walking caused by plantarflexors dynamic or static contracture. The results of this study show that primarily ankle and knee moments and powers are the features that should be carefully inspected as they exhibit distinct differences in the mid and terminal stance, which indicate the degree of SOLGAS in a particular pathological case. These features can serve as strong indicators of which muscle is predominantly responsible for foot equinus and can, combined with the data from clinical examination of a particular patient, importantly enhance reliability of determination of the predominant cause of toe-walking.

#### 4.3. Comparison to self-induced toe-walking

Two studies examined kinematics and kinetics of toe-walking that was self-induced by neurologically intact subjects (Kerrigan et al., 2000; Perry et al., 2003) and contrasted it to walking in normal conditions, yielding very similar results. The NW angle, moment and power patterns reported in both studies are entirely in agreement with the results of present study for experimental condition NW. Kerrigan et al., 2000 in their study reported on ankle, knee and hip moments and powers while Perry et al., 2003 reported on ankle and knee angles, moments and powers. Ankle moment trajectories in both studies are similar to our results for experimental conditions GAS and SOLGAS. There was a difference between the results of Kerrigan et al., 2000 and Perry et al., 2003 regarding ankle plantarflexion moment during preswing, where the subjects of Kerrigan et al., 2000 exhibited significantly lower peak as compared to the results of Perry et al., 2003 and our results for all three toe-walking experimental conditions. The ankle power trajectories in both studies are similar to our results for SOLGAS experimental conditions. In contrast the knee angle, moment and power trajectories reported in both studies are qualitatively similar to our results for only SOL experimental condition. The above discrepancy in the ankle and knee kinematic and kinetic patterns demonstrates that able-bodied individuals adopt rather peculiar form of toe-walking. According to our results able-bodied toe-walking, as reported in Kerrigan et al., 2000 and Perry et al., 2003, is such that soleus muscle is dynamically “contractured” through the whole stance phase, while the gastrocnemius muscle only assists in ankle moment increase during the loading response and midstance phases of gait cycle. This suggests that able-bodied walking might not be the appropriate model to study pathological toe-walking and to base diagnostics and treatment decisions upon its findings.

#### 4.4. Possible compensatory advantages of toe-walking

When interpreting gait records from a particular patient one should be also aware of potential compensatory advantages of toe-walking. Similar kinematic and kinetic gait patterns can also be recorded when primary cause for equinus and toe-walking is not due to contracture of triceps surae muscle group but rather compensation for pathological functioning of other muscles. For example if a particular patient has weak knee extensors that would prevent him or her from walking, the deficit of the required knee extension moment in the midstance could be compensated by “dynamic contracture” of otherwise unimpaired soleus, resulting in the gait patterns similar to those presented

for SOL experimental condition. Also in toe-walking the need for dorsiflexion moment during loading response is diminished. Therefore, patients with impaired tibialis anterior could resort to any of the three toe-walking conditions. Both of these possible compensatory advantages of toe-walking were suggested by Kerrigan et al., 2000 and the results of our study confirm their suggestion. From the results of present study we can propose another possible compensatory advantage of toe-walking. If a particular patient has weak hip flexors all three toe-walking conditions reduce a need for the hip flexor moment and power requirements during stance and preswing phases. In all these cases a clinician must establish neurological state of each muscle in order to correctly interpret the resulting gait pattern. The results of our study suggest that only sensible and practical compensatory advantages are obtained in toe-walking that results from increased soleus output during stance phase since gastrocnemius static or dynamic contracture puts additional strength requirements on the knee extensors.

#### 4.5. Methodological considerations

Standard deviations of the ankle, knee and hip angles, moments and powers trajectories obtained under the SOL, GAS and SOLGAS experimental conditions were similar to those obtained under NW condition, demonstrating the appropriateness of methodology used. Lengths, elasticity and number of elastic ropes used in toe-walking experimental conditions were selected in order to achieve equinus resulting in true toe-walking (not foot flat at the initial contact) and at the same time to allow subjects comfortable walking. This is the reason for selecting three shorter ropes for SOL, three longer ropes for GAS and only two shorter and two longer ropes for SOL experimental conditions. Therefore, the numerical comparisons between different toe-walking conditions should not be regarded as the absolute measure for quantification of differences as it is very difficult to “normalize” the degree of toe-walking among the three tested experimental conditions (SOL, GAS and SOLGAS) since all three have different biomechanical consequences. Rather, qualitative differences and distinct characteristics in particular kinematic and kinetic patterns should be noted, and they were stressed throughout the paper. The six subjects who participated in the study very carefully matched for their age, height and weight in order to minimize variability. The analysis of the results was restricted to the sagittal plane, the dominant plane of the action of triceps surae muscle group, which was considered so also in other similar studies (Kerrigan et al., 2000; Neptune et al., 2001; Perry et al., 2003).

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