Musculo-tendon length and lengthening velocity of rectus femoris in stiff knee gait

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Abstract

Inappropriate activity of M. rectus femoris (RF) during swing is believed to contribute to stiff knee gait in cerebral palsy. This study used musculoskeletal modeling techniques to analyze rectus femoris musculo-tendon (MT) length and lengthening velocity during stiff knee gait in 35 children with diplegic cerebral palsy (CP). Duncan Ely test scores were used to categorize the patients into four groups with increasing levels of rectus femoris spasticity. Knee kinematics confirmed a significant reduction and delay of maximal peak knee flexion during swing in the patient groups compared to reference values. Maximal musculo-tendon length of M. rectus femoris was reduced and occurred prematurely in swing. Musculo-tendon lengthening velocity was significantly reduced and the timing of the maximal lengthening velocity was shifted into stance phase.

The present study demonstrates altered dynamic behavior of the M. rectus femoris in stiff knee gait and the results indicate that maximal knee flexion in swing was not a valid reference for the MT length of the M. rectus femoris. Furthermore, in the patient group maximal musculo-tendon lengthening velocity of the muscle related to the stance phase rather than the stance–swing transition.

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1. Introduction

During normal steady state gait, M. rectus femoris (RF) is briefly active during the stance–swing transition to restrain knee flexion [1]. In children with cerebral palsy (CP), spasticity of the rectus femoris muscle with consequent prolonged activity in swing phase, is thought to restrict knee flexion during swing [2–8]. In clinical practice, Duncan Ely testing is used to assess spasticity in the M. rectus femoris. With the patient lying prone, the examiner rapidly flexes the knee passively. The rapid movement stretches the rectus femoris muscle and tests the velocity-dependent spasticity of the muscle. The test is considered positive if the examiner feels excessive resistance or the ipsilateral hip flexes [8]. Recent work has suggested that the test is predictive of

rectus femoris dysfunction during gait [9]. During stiff knee gait, the onset of knee flexion at the stance–swing transition is thought to trigger excessive and prolonged muscle activity in response to muscle stretch. Consequently, an inappropriate knee extension moment is generated by the rectus femoris during the stance–swing transition and the remainder of swing [3,5].

The contribution of the M. rectus femoris to stiff knee gait in CP remains unclear. Although a causal relation between increased RF activation and reduced peak knee flexion in swing has been confirmed using forward simulation techniques [10,11], recent studies indicate that reduced knee flexion velocity at toe-off may be the dominant cause of diminished knee flexion amplitude during swing in children with CP [12].

The presence of muscle stretch is key issue for a potential contribution of hyper-reflexia in triggering inappropriate rectus femoris at the stance–swing transition. However,

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there is little in the literature on changes in musculo-tendon length or lengthening velocity of the M. rectus femoris muscle during normal or stiff knee gait [13].

The aim of the present study was to analyze the dynamic behavior of the rectus femoris musculo-tendon (MT) lengthening and MT lengthening velocity during stiff knee gait in CP patients compared to normals. We hypothesized that MT lengthening and lengthening velocity of the M. rectus femoris are diminished in patients with stiff knee gait compared to normals and that these changes can be related to clinical measures of spasticity.

2. Methods

2.1. Patients

This retrospective study examined gait kinematics, MT lengths and MT lengthening velocities of 60 limbs in 35 patients (aged 6–10 years old, average 7 years, S.D.: 4.5 months) with a confirmed diagnosis of spastic diplegia who presented with stiff knee gait. Stiff knee gait was evaluated clinically as a reduction and/or delay of peak knee flexion during swing phase and presenting prolonged activity of the M. rectus femoris in swing phase and a DE score exceeding 1. All children were independent ambulators and none had been treated previously with orthopaedic surgery or received Botulinum toxin injections within 6 months before gait analysis. Modified Ashworth scores were used for assessing the degree of resistance felt during the Duncan Ely test (Table 1). Based on these, four subgroups (DE 1, 1.5, 2 and 3) were identified, each including 15 limbs.

2.2. Data analysis

Gait assessment was performed in the clinical motion analysis laboratory of Pellenberg (University Hospital-Leuven), using a three-dimensional movement analysis system (VICON), force plate recordings (AMTI) and surface EMG recordings from 14 muscles. Lower limb joint kinematics and kinetics were calculated using Vicon Clinical Manager. For each patient, three representative trials were selected. Maximum peak knee flexion during swing (MPF) and the timing of peak knee flexion (% of the Gait cycle, T_{MPF}) were noted. Hip angle coinciding with maximal peak knee flexion (HFL_MPF) as well as the angle

coinciding with maximal MT length (L_{max}) were analyzed (HFL_ L).

The musculo-tendon length of M. rectus femoris was calculated for each trial using a four-segment musculoskeletal model defined using SIMM (software for musculoskeletal modeling, [15]). The model allowed for three degrees of freedom (DOF) at the hip and one DOF at the knee taking into account the tibiofemoral and patellofemoral kinematics [16]. The inputs to the model were the joint kinematics of knee (flexion/extension) and hip (flexion/extension, ab-/adduction, internal and external rotation) obtained during three strides. The model used average adult skeletal morphology. All calculated musculo-tendon lengths were normalised with respect to the musculo-tendon length in the anatomical reference position (hip and knee angles 0°).

Based on the musculo-tendon length profiles, length at toe-off (L_{Sw}) and maximum length during swing (L_{max}) were derived for each individual trial. (Fig. 1A). Furthermore, the timing of the maximum length during swing was noted (% of the gait cycle, $T_{L_{max}}$).

Musculo-tendon lengthening velocity was calculated by numerically differentiating the MT length data with respect to time. For each trial, the maximal MT lengthening velocity (V_{max}) during the gait cycle was calculated and the timing (% of the gait cycle, $T_{V_{max}}$) was recorded (Fig. 1B).

Reference values for musculo-tendon length and lengthening velocity of M. rectus femoris were calculated based on the gait kinematics of a normal data set ($n = 20$, average age 8 years, S.D.: 6 months).

The differences between the parameters of the patient groups and the controls were studied using ANOVA. A Tukey test was performed to test the significance of the differences between the different subgroups (Statistica 6.1). A critical p -value of 0.05 was selected.

3. Results

Table 2 presents an overview of the results of the statistical analysis for the different parameters studied.

3.1. Spatio-temporal parameters

Walking velocity (Vel) was significantly lower in the patient groups compared to normals ($p < 0.05$). Only limited differences in walking velocity were found for the different patient groups (Table 2). Timing of toe-off

Table 1
Modified Ashworth score [14]

0	No increase in muscle tone
1	Slight increase in muscle tone, manifested by catch and release, or by minimal resistance at the end of the range of motion
1.5	Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the ROM
2	More marked increase in muscle tone through most of ROM but affected part(s) easily moved
3	Considerable increases in muscle tone, passive movement difficult
4	Affected part(s) rigid in flexion or extension

Fig. 1. (A) Musculo-tendon length and (B) musculo-tendon lengthening velocity during the gait cycle in the normal population (NORM) and different patient groups (DE 1, 1.5, 2 and 3). Length is normalised for the length in the anatomical reference position (hip and knee angle: 0°).

(ST_SW) was comparable in the control population and the patient groups (Fig. 2). A trend towards increased duration of the stance phase could be observed for the patient groups presenting the highest spasticity level (Fig. 2).

3.2. Knee kinematics

Stiff knee gait was confirmed for the patient group. Mean peak flexion (MPF) decreased significantly in all patient populations compared to the normal control population ($p < 0.05$). Between the adjacent subgroups, significant differences were only found between DE 1.5 and 2 ($p < 0.05$, Fig. 3). Timing of the peak knee flexion (T_{MPF}) indicated a significant delay of the maximum peak knee flexion in the patient groups compared to the normative population ($p < 0.05$). With increasing score for DE, maximum peak knee flexion occurred later in swing. However, for adjacent subgroups, significant

differences were only found between DE 1.5 and 2 ($p < 0.05$, Fig. 2).

3.3. Musculo-tendon length and lengthening velocity

Fig. 1 shows the lengthening (A) and lengthening velocity (B) of the rectus femoris, normalised for the gait cycle in the normal population and the different patient groups. MT length is normalised for the M. rectus femoris MT length in the anatomical position i.e. with hip and knee fully extended. In the control population, the MT lengthening profile is characterized by a gradual lengthening of the muscle after initial contact. Maximal musculo-tendon length is attained during initial swing, after which the muscle shortens during the remainder of swing.

Maximal MT length of M. rectus femoris during swing (L_{max}) was significantly shorter in the patient group compared to the control population ($p < 0.05$). A significant

Table 2

Average value for the studied parameters in the different groups

	Norm	DE 1	DE 1.5	DE 2	DE 3	Compared to normals				Between adjacent categories			Others		
						0–1	0–1.5	0–2	0–3	1–1.5	1.5–2	2–3	1–2	1–3	1.5–3
Vel (m/s)	1.355	0.834	0.889	0.837	0.784	*	*	*	*	ns	ns	ns	ns	ns	ns
ST_SW (%)	64.67	64.71	64.05	65.98	66.37	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
Str_D (s)	0.986	0.83	0.948	1.01	0.91	*	ns	ns	ns	ns	ns	*	*	ns	ns
MPF (°)	56.56	51.50	51.24	42.64	47.34	*	*	*	*	ns	*	ns	*	ns	ns
T_MPF (%)	76.93	79.6	80.7	84.0	84.44	*	*	*	*	ns	*	ns	*	*	*
LIC (%)	93.17	95.37	95.6	94.99	96.18	*	*	*	*	ns	ns	*	ns	ns	ns
L _{Sw} (%)	106.12	104.24	103.74	102.71	102.59	*	*	*	*	ns	*	ns	*	*	*
L _{max} (%)	107.43	104.76	103.99	102.87	102.72	*	*	*	*	*	*	ns	*	*	*
T _{Lmax} (%)	71.29	66.65	67.1	68.08	68.53	*	*	*	*	ns	ns	ns	ns	ns	ns
V _{max_L} (m/s)	0.175	0.219	0.155	0.144	0.161	*	ns	*	ns	*	ns	ns	*	*	ns
T _{Vmax_L} (%)	61.81	56.6	51.61	47.68	47.11	*	*	*	*	*	ns	ns	*	*	ns
HFL_L (degree)	10.05	6.79	12.13	10.52	13.88	*	ns	ns	*	*	ns	ns	ns	*	ns
HFL_MPF (degree)	20.94	31.23	33.29	34.88	38.33	*	*	*	*	ns	ns	*	ns	*	*

Statistical significance of the differences between normal (norm) and patient groups (DE 1, 1.5, 2 and 3) as well as between adjacent patient groups. Critical p -value: 0.05, ns: $p > 0.05$.

* $p < 0.05$.

decrease of maximal MT length with increasing DE score was found for adjacent patient groups, with the exception of DE 3. MT length at toe-off (L_{Sw}) was significantly shorter in the patient groups compared to normals ($p < 0.05$). Although a tendency towards shorter lengths with increasing DE score was present, significant differences were only found between the patient groups with DE 2 and 3 (Fig. 4).

The timing of maximal MT length (T_{Lmax}) was shifted towards the stance–swing transition in the patients compared to the normative population ($p < 0.05$). However, no significant differences between the different patient categories were found (Fig. 2).

Maximal MT lengthening velocity of the M. rectus femoris (V_{max_L}) was significantly higher in the patient groups presenting DE 1 ($p < 0.05$) compared to controls and other patient groups ($p < 0.05$). Although for the patient groups with DE 1.5–2 and 3, the maximal MT lengthening velocity was lower than the control population, this finding was only significant for the groups with DE 2 ($p < 0.05$, Fig. 5).

The timing of the maximal MT lengthening velocity during the gait cycle (T_{Vmax}) was altered in all patient groups compared to normals, presenting a tendency to more premature values with increasing score for DE. However, for

Fig. 2. Comparison of timing of toe-off (◆—ST_SW, % GC), timing of maximal peak knee flexion (▲—T_MPF, % GC), timing of maximal musculo-tendon length (■—T_Lmax, % GC) and timing of the maximal lengthening velocity (●—T_Vmax_L, % GC) for the control population (NORM) and the different patient groups (DE 1, 1.5, 2 and 3).

Fig. 3. Peak knee flexion angle (—▲— MPF), hip flexion angle coinciding with maximal musculo-tendon length of the rectus femoris (—◆— HFL_L, degree) and maximal peak knee flexion (—■— HFL_MPF, degree) in the control population (NORM) and different patient categories (DE 1, 1.5, 2 and 3).

adjacent groups, this finding was only significant for the groups presenting DE 1 and 1.5 ($p < 0.05$, Fig. 2).

3.4. Hip kinematics

Hip flexion angle coinciding with maximal length (HFL_L) was significantly higher only in the patients presenting DE 3 compared to normals ($p < 0.05$). Between adjacent groups, this was only significantly different for the patients presenting DE 1 and 1.5 (Fig. 3). Hip flexion position coinciding with maximal knee flexion during swing (HFL_MPF) was significantly higher in all patient

categories compared to normal control subjects. Although a trend towards increased hip flexion could be observed with increasing spasticity level of the rectus femoris, no significant differences between adjacent patient groups were observed (Fig. 3).

4. Discussion

During normal gait, knee flexion amplitude is crucial for toe clearance and unobstructed swing through the swing limb [17]. A decreased knee flexion amplitude of the swing

Fig. 4. Comparison of the maximal musculo-tendon length in swing (—■— L_{max}) and musculo-tendon length at toe-off (—◆— L_{SW}) for the control population (NORM) and the different patient groups (DE 1, 1.5, 2 and 3). Length is normalised for the length in the anatomical reference position (hip and knee angle: 0°).

Fig. 5. Maximal muscle lengthening velocity (m/s) in the control population and different patient groups (DE 1, 1.5, 2 and 3).

limb hinders toe clearance and therefore introduces the need for energy inefficient compensatory movements to allow unobstructed swing limb advancement.

Although the clinical manifestation is straightforward, the cause of stiff knee gait is still unclear. Analysis of surface electromyography of the M. rectus femoris, shows excessive and prolonged activation into swing phase. This abnormal activity of the rectus femoris is thought to limit knee flexion by producing an excessive knee extension moment during swing [2,5]. More recently, dynamic analysis of stiff knee gait revealed that weakness of the hip flexors or plantar-flexors [18] or factors reducing knee flexion velocity in double support [19] will influence the knee flexion during swing.

Due to its bi-articular nature, the effect of the simultaneous changes in angles at the hip and knee on musculo-tendon length needs to be taken into account when considering changes in muscle length. Therefore, musculoskeletal modeling techniques were used to calculate musculo-tendon length given a specific geometrical configuration, i.e. a set of joint angles. The musculoskeletal model used in this study was the standard SIMM model [15]. The muscle lengths derived from the model therefore describe the length of the musculo-tendinous unit for a given geometric configuration of the limb segments. No adaptations were made to reflect paediatric or pathological morphology. Therefore, the presence of an aberrant patella position (e.g. patella alta) often associated with spasticity or contracture of the M. rectus femoris will not be reflected in the results of the present study.

The musculo-tendon length profile of rectus femoris in the control group documents gradual lengthening of the muscle during stance. Maximal lengthening of the muscle is attained around 76% of the gait cycle. Patient data confirms

that stiff knee gait is associated with a significant reduction of the maximal rectus femoris MT length in swing. In the patient group, minimal additional lengthening of the rectus femoris muscle after toe-off is seen; with maximal muscle length achieved shortly after toe-off. As rectus femoris is a bi-articular nature muscle, changes in MT length need to relate both knee and hip kinematics simultaneously. At the instant of maximal muscle length of the rectus femoris, hip flexion was not significantly increased in the patient group from the controls (with the exception of the patients with the highest spasticity score). However, at the instant of maximal knee flexion, hip kinematics revealed significantly higher hip flexion compared to the controls. Although other factors may induce increased hip flexion, these findings suggest that the higher hip flexion will assist in attaining more knee flexion in swing without further increase in the MT length of M. rectus femoris.

It is important to emphasize that peak knee flexion per se is not a good indicator of M. rectus femoris MT length in children with cerebral palsy with stiff knee gait. Whereas peak knee flexion is delayed in stiff knee gait, the timing of maximal rectus femoris MT length was shifted towards toe-off, with maximal knee flexion being associated with increased hip flexion. Therefore, knee and hip flexions amplitude at toe-off may be a better reflection of rectus femoris MT length.

MT lengthening velocities were slower in the patient group, except for the group with the least spasticity. A more marked finding however was the more premature occurrence of the maximal MT lengthening velocity, shifting this event from around toe-off in the control population closer to mid stance in the patient group.

In the presence of motor control disorder, musculo-tendon length and velocities may reflect altered neurophysi-

siologic control and its effect on the dynamic behavior of bi-articular muscles. The significant reduction of the maximal musculo-tendon length indicates limited excursion of the musculo-tendon unit, which complies with reflexive muscle contraction in response to rapid stretch as seen in the DE test. Likewise, the observed reduction of the maximal musculo-tendon lengthening velocity potentially reflects the restraining action of rectus femoris that will limit further the rate of change of the musculo-tendon length. It is important to note that whereas in the control population, maximal lengthening velocity occurred just before toe-off, within increasing levels of spasticity of the rectus femoris, maximal lengthening velocity shifted more into the stance phase. This finding indicates that the trigger for reflexive activation of the rectus femoris is most likely to occur during stance phase and not during the stance–swing transition.

The reported changes in MT length and MT lengthening velocities do not contradict the findings of the dynamic simulations. The effect of reduced knee flexion velocity as described by Goldberg et al. [19] was not explored explicitly, but may be reflected indirectly in the reduced musculo-tendon lengthening velocity. It should be noted that MT lengthening velocity would also be affected by altered hip joint velocities. However, the reported changes in hip joint kinematics to achieve peak knee flexion seems to suggest that some restraining action on muscle lengthening may be present and contributing to the observed phenomenon.

It is important to consider the effect of walking speed on the observed findings in view of the significant different walking speeds in the normals (1.355 m/s) compared with the patients (DE 1: 0.834 m/s, DE 1.5: 0.889 m/s, DE 2: 0.837 m/s and DE 3: 0.784 m/s). Even in normals, reduced walking velocity reduces the amount of knee flexion amplitude in swing. Van der Linden et al. [20] reported a reduction of approximately 20° between two extreme walking velocities in a group of children. This would account for a reduction of the MT length by 3.5%. This is lower than the average differences in MT length compared to the control population found in our study, with the exception of the least involved group, DE 1 (Norm-DE 1: 2.66%, Norm-DE 1.5: 3.5%, Norm-DE 2: 4.56%, Norm-DE 3: 4.7%). In addition, Van der Linden et al. [20] reported a reduction of hip extension of 5° at toe-off and hip flexion before initial contact due to reduced walking speed. This would account for a change in MT length of less than 1%. However, at the instant of peak knee flexion no effect of walking velocity on hip kinematics was reported and would therefore not affect further the reported difference in MT length. Apart from reduced magnitude, changes in timing of the maximal MT length and lengthening velocity were seen in our patients. In addition, the positive Duncan Ely and presence of prolonged activity further confirms the presence of rectus femoris dysfunction.

The present study failed to relate the different levels of spasticity as measured clinically to significant differences in

the kinematics or MT length and lengthening velocity of the different sub-groups, as would have been reflected in significant differences between the adjacent patient groups. However, for the patient groups presenting DE 1.5, 2 and 3, most parameters were significantly different from the control population. These observations underline the inability to differentiate clearly between successive levels of spasticity. Comparing Ashworth scores with instrumented measures. Damiano et al. [21] reported good agreement of the Ashworth scores at the extremes of the scale, but marked inconsistencies in mid-range values were found. Better techniques for evaluating spasticity to muscle dynamics during functional activities are required in the future.

5. Conclusion

Despite the multi-factorial determination of stiff knee gait, the present study documents aberrant MT lengthening and lengthening velocities of the M. rectus femoris during stiff knee gait. Restriction of musculo-tendon lengthening in swing is documented. The uncoupling of maximal muscle length and peak knee flexion is important when considering rectus femoris muscle length based on knee flexion angles only. In the patient group, peak muscle-tendon length was associated with initial more than mid-swing. The results of the present study additionally indicate that the musculo-tendon lengthening velocity of the muscle is reduced, with the peak value associated to stance phase rather than stance–swing transition.

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