Muscle length and lengthening velocity in voluntary crouch gait

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Abstract

The purpose of this study was to explore how origin-insertion length and lengthening velocity of hamstring and psoas muscle change as a result of crouch gait. The second purpose was to study the effect of changes in walking speed, in crouch, on muscle lengths and velocities. Eight healthy female subjects walked on a treadmill both normally and in crouch. In the crouch condition, subjects walked at three different walking speeds. 3D kinematic data were collected and muscle lengths and velocities were calculated using musculoskeletal modeling. It was found that voluntary walking in crouch resulted in shorter psoas length compared to normal, but not in shorter hamstrings length. Moreover, crouch gait did not result in slower muscle lengthening velocities compared to normal gait. These results do not support the role of hamstrings shortness or spasticity in causing crouch gait. Decreasing walking speed clearly reduced muscle lengths and lengthening velocities. Therefore, patients with short or spastic muscles are more likely to respond by walking slower than by walking in crouch. Also, differences in walking speed should be avoided as a confounding factor when comparing patient groups with controls.

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1. Introduction

Crouch gait, a gait pattern characterized by excessive knee flexion in terminal swing and stance, is a frequently observed gait deviation among children with cerebral palsy (CP). No unambiguous definition of crouch gait is present in the literature. According to Perry [1], ‘excessive knee flexion’ in loading response is present when knee flexion is greater than 25° and ‘inadequate extension’ in mid stance and terminal stance when knee flexion remains greater than 10°. Often times, a threshold value is used of 20° of minimal knee flexion during stance [2] or at initial contact (IC) [3,4]. Crouch gait in children should be subjected to treatment, as knee and hip flexion angles tend to increase with age due to increasing body weight, ultimately resulting in the loss of independent walking [5].

It is not well understood why many children with CP walk with excessive knee and hip flexion. Possible causes of crouch gait are short or spastic muscles. Especially contracture and spasticity of the hamstring muscles are often mentioned as possible causes of a flexed-knee gait pattern [1,6–8]. However, contractures or spasticity in other muscles such as the psoas may also contribute to crouch gait [2].

So far, studies of the role of hamstrings length and velocity in crouch gait have been inconclusive. In a modeling study, Delp et al. [2] found that in only 3 of 14 children with spastic CP walking in crouch, the hamstrings operated at shorter maximal muscle length than in healthy children. Thus, functional hamstrings length was adequate in most children, indicating that hamstrings contracture may not be the cause of crouch gait. In all children, the psoas muscle was shorter than normal during gait [2]. This could indicate that hip contractures may be a primary cause of crouch, although these could also be the result of compensation. In 1998, Thompson et al. [9] had similar findings, showing that only 4 of 18 limbs had shorter hamstrings length during crouch gait than normal. Arnold et al. [3] also found that 35% of 152 CP patients walking in crouch had short hamstrings during gait. However, another 30% had not short but ‘slow’ hamstrings compared to normal. Surgically lengthening these short and/or slow...
muscles improved knee extension in terminal swing in most cases [3,4], indicating that a relationship between hamstrings length and knee extension does exist. Thus, the exact relation between hamstrings length, hamstrings velocity and the severity of crouch gait remains unclear.

Moreover, all studies that have investigated muscle lengths and velocities during crouch gait show a number of compromising factors. First, muscle lengths and velocities in children with CP are compared to those in healthy children, walking at comfortable walking speed. As children with CP tend to walk slower than healthy children, walking speed in itself may have a large effect on hamstrings lengths and velocities. Second, a lot of variation usually exists among the gait patterns of CP patients. For example, in the studies of Arnold et al. [3,4] both children with “jump knee” gait and with persistent crouch during stance were included. Third, variations may have existed between patients in their clinical history and in previous surgical procedures. All these factors obscure a clear view on the relation between hamstrings length and crouch gait.

In order to look at the effects of crouch gait without any interfering factors, healthy subjects walking in crouch can be used as a model. In this way walking speed can be controlled, and there are no side effects of pathologies or uncontrolled compensations. It also eliminates inter-subject variance, as all conditions can be performed by the same subjects. Healthy subjects have previously been used successfully as a model for pathological gait in children with CP [10–14], but with different purposes.

The purpose of the current study was to examine how muscle lengths and velocities change as a result of walking in crouch. We focused on three muscles that are commonly suspected to cause crouch gait in children with CP: psoas, semitendinosus and biceps femoris. We hypothesized that these muscles would show shorter than normal peak lengths and slower than normal peak lengthening velocities during crouch gait.

Second, we studied the effect of different walking speeds, in crouch, on muscle lengths and velocities. We expected that decreasing walking speed would decrease muscle lengths and lengthening velocities.

2. Methods

2.1. Subjects

Eight healthy female subjects were included in this study. The characteristics of the subjects (±S.D.) were as follows: age 22.1 years (±1.1); weight 61.8 kg (±6.5); length 1.70 m (±0.06). A provided informed consent.

2.2. Design

The subjects walked on a treadmill both normally and in crouch. Normal gait (NORM) was performed at self-selected comfortable walking speed (CWS), which was measured beforehand while walking over ground on a 50 m track. Crouch gait was performed at this same speed with 20° of knee flexion at midstance (CWS20) and with 30° of knee flexion at midstance (CWS30). Deep crouch (30° flexion) was also performed at walking speeds of 0.8, 1.1 and 1.4 m/s (SLOW30, MID30 and FAST30). The knee flexion angle was set with a goniometer while standing, while a rope was tightened mediolaterally in front of the subjects, at eye-height. During walking, subjects were instructed to keep this rope in front of their eyes, to keep the trunk upright and not to walk on their toes. Other than that they were free to walk as they preferred. They walked in each condition for 4 min, in order to accommodate to the new situation. The recordings of the final minute were used for analysis.

2.3. Kinematics

3D kinematic data were collected for the pelvis, thigh, shank and foot of the right leg, using a motion capture system (Optotrak, Northern Digital, Waterloo, Canada). A technical cluster of three markers was attached to each segment. While standing in anatomical position, fifteen anatomical landmarks were indicated in order to anatomically calibrate the technical cluster frames [15]. These were for the pelvis: the left and right anterior and posterior superior iliac spines; for the thigh: the greater trochanter and the medial and lateral epicondyle; for the shank: the tibial tuberosity, the head of the fibula and the medial and lateral malleolus; and for the foot: the calcaneus and the first, second and fifth metatarsophalangeal joints.

2.4. Data analysis

3D kinematic data were analyzed using custom made software (BodyMech, Matlab®, The Mathworks). Initial contact (IC) and toe-off (TO) values were calculated using the forward foot velocity, and defined as the instants where this velocity became lower (IC) or higher (TO) than 20% of its maximal value. This method was derived comparing kinematic data with force plate data in previous experiments. Kinematic data were divided into strides from IC to IC. The first 10 strides of the final (fourth) minute of each trial were taken for further analysis. Joint and segment angles were calculated following the CAMARC anatomical frame definitions [16]. The spatio-temporal parameters stride length, stride frequency and the percentage of stance time in the total gait cycle were also calculated. The data were normalized to time per stride, yielding normalized time of 0–100% of gait cycle, and averaged over 10 strides for each subject. Mean knee angles during 0–50% of the gait cycle, covering loading response, midstance and terminal stance and excluding rapid knee flexion in pre-swing, were calculated and used as a measure of crouch.

SIMM modeling software [17] was used to calculate muscle–tendon complex lengths for three muscles. These were the main muscles that are often spastic or contracted in children walking in crouch, i.e. psoas, semitendinosus and biceps femoris (long head). Semimembranosus was not analyzed as this muscle operates at similar muscle length as the semitendinosus during walking [18,19]. The SIMM standard generic model was used and scaled to the individual subject sizes, using 3D kinematic data from the anatomical landmarks. Muscle lengths were differentiated to obtain muscle velocities. Both muscle lengths and velocities were normalized to time and averaged over 10 strides for each subject. Peak muscle length and lengthening velocities were calculated and statistically analyzed for all muscles.
2.5. Statistics

A repeated measures analysis of variance (ANOVA), with Bonferroni adjustment for multiple comparisons as post hoc test, was used to investigate the effects of crouch gait and walking speed on kinematics, spatio-temporal parameters, muscle lengths and velocities. \( P \)-values less than 0.05 were considered statistically significant. If the sphericity assumption was not met, a Huynh-Feldt adjustment was used.

3. Results

3.1. Effects of walking in crouch

Fig. 1 shows a schematic illustration of one subject walking both normally and in CWS30. For a proper interpretation of the muscle length data, we performed two checks on the measured data. First it was investigated whether the subjects performed crouch gait with knee flexion as intended. Fig. 2 shows segment and joint angles for NORM, CWS20 and CWS30, averaged over all subjects. CWS was 1.41 ± 0.14 m/s. Mean knee angles averaged over 0–50% of gait cycle were 12.6 ± 2.8°; 18.2 ± 4.7° and 27.3 ± 6.7° for NORM, CWS20 and CWS30, respectively (\( p < 0.001 \)), which shows that knee angles increased with crouch as imposed. Hip flexion and ankle dorsiflexion during the stance phase increased significantly with crouch (\( p = 0.001 \) for both hip and ankle), whereas sagittal pelvis and foot angles relative to the global reference frame remained constant (\( p = 0.23 \) and \( p = 0.79 \), respectively).

Second, the effects of crouch gait on spatio-temporal parameters were investigated. Table 1a shows stride length, stride frequency and the percentage of stance time during the gait cycle. No significant differences were found for any of these parameters between NORM, CWS20 and CWS30. Therefore, possible differences in muscle lengths or velocities can be attributed to differences in kinematics, not to differences in stride length or duration.

Muscle lengths of the psoas, semitendinosus and biceps femoris muscles during normal and crouch gait are shown in Fig. 3A–C. The psoas acted at significantly shorter length during the crouch conditions compared to normal, due to differences in hip angle. The bi-articular hamstring muscles on the other hand, showed hardly any differences between normal and crouch gait. Although peak semitendinosus length showed a tendency to increase, it did not change significantly with crouch (\( p = 0.12 \)). The same was true for the peak length of the biceps femoris longus (\( p = 0.06 \)).

Muscle velocities of the same three muscles during normal and crouch gait are shown in Fig. 3D–F. Most surprisingly, peak semitendinosus and biceps femoris longus lengthening velocity increased with crouch gait (\( p < 0.001 \)). Peak psoas lengthening velocity did not change significantly with crouch (\( p = 0.15 \)), while the average lengthening velocity during stance increased (\( p = 0.012 \)).

3.2. Effects of different walking speeds during crouch gait

Again, it was first examined whether the SLOW30, MID30 and FAST30 conditions were performed as intended. Knee flexion angles during stance for the three conditions were 31.1 ± 9.3°, 26.6 ± 7.2° and 26.4 ± 6.8°, respectively. Thus, knee flexion in SLOW30 was approximately 5° higher than in the other two conditions (\( p = 0.02 \)).

Table 1b shows spatio-temporal parameters for the SLOW30, MID30 and FAST30 conditions. As could be

| Spatio-temporal parameters of normal and crouch gait |
|---|---|---|
|   | NORM\(^a\) | CWS20\(^b\) | CWS30 |
| Stride length | 1.45 ± 0.11 | 1.42 ± 0.11 | 1.44 ± 0.14 |
| Stride frequency | 0.97 ± 0.04 | 1.00 ± 0.05 | 1.01 ± 0.07 |
| % Stance | 61.0 ± 2.4 | 60.5 ± 2.2 | 60.4 ± 1.6 |

\(^a\) NORM, normal gait.  
\(^b\) CWS, comfortable walking speed; 20 and 30 indicate average knee flexion angles in stance.

| Spatio-temporal parameters of crouch gait at different walking speeds |
|---|---|---|
| SLOW30 | MID30 | FAST30 |
| Stride length | 1.07 ± 0.15 | 1.25 ± 0.16* | 1.41 ± 0.10** |
| Stride frequency | 0.79 ± 0.11 | 0.90 ± 0.11* | 0.99 ± 0.07** |
| % Stance | 65.5 ± 1.2 | 63.6 ± 2.0* | 61.0 ± 2.1** |

* Significantly different from SLOW30.  
** Significantly different from SLOW30 and MID30.
expected, both stride length and stride frequency decreased with decreasing walking speed ($p < 0.001$). Also, stance percentage increased with decreasing walking speed ($p < 0.001$).

Fig. 4A–C shows muscle lengths for the psoas and hamstring muscles during the three different walking speeds in crouch. The excursion (maximal length minus minimal length) of all muscles decreased with decreasing walking speeds. Peak length of semitendinosus ($p = 0.04$), biceps femoris ($p = 0.03$) and psoas ($p = 0.004$) all decreased with decreasing walking speed.

Fig. 4D–F shows the muscle velocities during the three different walking speeds in crouch. Not surprisingly, all velocities clearly decreased with decreasing walking speed.

4. Discussion

The main goal of this study was to investigate how muscle lengths and velocities change as a result of crouch gait. These findings might contribute to the discussion on why cerebral palsy patients walk in crouch. It was hypothesized that hamstrings and psoas would operate at shorter lengths and/or slower lengthening velocities during crouch, because this would indicate that muscle shortness and/or spasticity could be the cause of crouch gait. However, only psoas functioned at shorter length during crouch, and none of the muscles showed slower lengthening velocities in crouch.

Additionally, the effect of different walking speeds, in crouch, on muscle lengths and velocities was studied. It was shown that both hamstrings and psoas muscles functioned at shorter muscle lengths and at lower lengthening velocities when walking speed was decreased.

We used healthy subjects as a model, which enabled us to look specifically at the effects of a crouched position during gait. In comparison to crouch gait in patients with CP, simulated crouch gait is not influenced by inter-individual differences and has no side effects of pathologies or uncontrolled compensations. Furthermore, the use of healthy subjects made it possible to control for walking speed. On the other hand, there may have been differences in the way healthy subjects performed crouch gait and the way patients typically walk in crouch. Our subjects walked at relatively high walking speed (CWS of 1.41 $\pm$ 0.14 m/s), whereas most patients walk substantially slower. These high walking speeds required large steps, resulting in knee angles at IC that were smaller than 20° in some cases. According to the definition of Arnold et al. [3,4] this would not be considered crouch gait. However, the crouched conditions still showed considerably more flexed knees than normal (Fig. 2), which allows for a meaningful comparison between the two gait types.

There may also have been a difference between our subjects and crouch walking patients in the positioning of the pelvis. Although our instructions to the subjects did not include a standardization of pelvic positioning, subjects appeared to walk in crouch with an unchanged pelvic position. If we assume that patients walk with spastic or short hamstrings, they may show posterior pelvic tilt in...
terminal swing, to prevent further lengthening of the hamstrings. It is also known that many patients walk in crouch with anterior pelvic tilt, especially in crouched gait patterns with equines [1]. Therefore, our results cannot be generalized to all crouch walking patients with CP, because patients are not uniform in their performance of crouch gait with respect to pelvic positioning. Our results do show however, that hamstrings length is not influenced by the degree of crouch gait, and thus that anterior or posterior tilting of the pelvis will influence hamstrings length independently of walking in crouch.

Furthermore, as all three muscles under study showed higher than normal muscle lengthening velocities in crouch, crouch gait does not seem to be a way to prevent spastic responses, i.e. velocity dependent hyper reflexes [20]. Based on the results of this study, only the psoas muscle functions at a shorter than normal length during crouch gait. Pure contracture of the psoas could therefore be hypothesized to

Fig. 3. (A–C) Muscle lengths and (D–F) muscle velocities for normal gait (NORM), 20° (CWS20) and 30° (CWS30) crouch gait for the psoas (PSO), semitendinosus (SMT) and biceps femoris caput longus (BFL) muscles. *Indicates a significant difference between the conditions.

Fig. 4. (A–C) Muscle lengths and (D–F) muscle velocities for slow (SLOW30), middle (MID30) and fast (FAST30) 30° crouch gait for the psoas (PSO), semitendinosus (SMT) and biceps femoris caput longus (BFL) muscles. *Indicates a significant difference between the conditions.
be a cause of crouch gait, while pure contracture of the hamstrings could not.

These results seem contradictory to the results of a study by Matjačić and Olenšek [14], who studied artificially induced crouch walking in healthy adults by means of a psoas and hamstrings contraction emulation system. They found that when hamstrings or psoas or both were ‘contracted’, a flexed gait pattern arose, although with differences between the conditions. However, although their artificial, exoskeletal hamstring was said to be constructed in such a way as to act in parallel with hamstrings muscles, no data on moment arms were given. From their pictures it can be derived that the moment arm about the knee is substantially larger than that about the hip, whereas anatomical studies show a smaller hamstrings moment arm about the knee [17,21]. These differences may explain the apparent contradictory results with our study.

Our results also show that reducing walking speed has a much larger effect on muscle lengths and lengthening velocity than walking in crouch. This indicates that lowering walking speed acts as an effective adaptation strategy to short or spastic muscles. The peak velocities of all muscles decreased almost linearly with walking speed, even though subjects walked with slightly higher knee flexion in the slowest walking condition. This result reinforces the results of others that differences in walking speed are an important confounding factor when comparing patient groups with controls [22–24].

The strong dependency on walking speed might explain why the results of the study of Arnold et al. [3,4] seem contradictory to our results. In their study, hamstrings length and velocity before and after surgery were compared for a large group of children with CP walking in crouch. They found that lengthening of those hamstrings that operated at short length or slow velocity pre-operatively resulted in increased length and velocity post-operatively in most cases, indicating that procedures were functionally effective. However, since no correction was made for walking speed, their results may, at least partly, be explained by differences in walking speed, rather than differences in flexed-knee gait.

A very important assumption in this study as well as in many other modeling studies [2–4,9], is that muscles are modeled as simple strings, acting between origin and insertion. Geometrical origin-insertion length might be a valid estimate for the total length of the muscle–tendon complex, especially when wrapping points are accounted for. However, recent findings have shown that inter-muscular connections exist, which result in myofascial force-transmission between muscles and the surrounding connective tissue [25]. These cross-bindings influence muscle behavior and may cause that distal hamstring lengthening or shortening around the knee is not directly related to hamstrings lengthening or shortening around the hip. In a flexed-knee gait pattern, both hip and knee are more flexed than during normal gait, and hamstring muscles might therefore act at a different relative length around hip and knee while having constant geometrical origin-insertion length. Future research to investigate such effects will require new, non-conventional, approaches in experimental and modeling techniques.

This study focused on describing muscle kinematics during crouch gait in healthy subject, in order to explore whether changes at this level could explain crouch gait in CP patients. Factors related to the kinetics of walking that might explain crouch gait are ignored in such an approach. For instance, weakness of the calf muscles is often mentioned as a main cause of crouch gait [1,26]. More comprehensive modeling of human gait, using forward simulation, will be needed to explore factors and their mutual dependency that fully explain crouch gait in CP.

5. Conclusions

It can be concluded that walking in crouch does not necessarily coincide with shorter than normal hamstrings length. Moreover, crouch gait does not result in lower muscle lengthening velocities compared to normal gait. In contrast, decreasing walking speed in crouch has a much larger effect on both muscle lengths and velocities. Therefore, patients with short or spastic muscles are more likely to respond by walking slower than by walking in crouch. Differences in walking speed should be considered, when comparing patient groups with controls. Comprehensive musculoskeletal modeling is required to further investigate possible causes of crouch gait.

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References


