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Gait characteristics following Achilles tendon elongation: the foot rocker perspective

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The action of three functional rockers, namely the heel, ankle and forefoot rocker, assist the progression of the leg over the supporting foot. The purpose of this case series was to analyze the occurrence of foot rockers during gait in three children with cerebral palsy (CP) who had undergone the tendo-Achilles lengthening (TAL), procedure followed by a clinic- or home-based intervention and in one child with CP without history of surgery. Self-selected gait was video-recorded in a laboratory during six testing sessions at half-year intervals rendering a 3 year period of observation. One child had pre- and post-surgical gait data and the other two had post surgical data only. Sagittal plane knee angular velocity, as well as foot to ground positions, and foot rocker occurrence were analyzed. In a child with history of CP, and without history of surgery, mean angular velocities of the 1st, 2nd and 3rd foot rocker were 3.7, 0.57 and 6.67 rad/s, respectively, and the step length and cadence were normal. In children who underwent TAL the 1st and 2nd rocker was absent, as the initial contact of the foot with the ground was either with foot-flat or forefoot. The mean velocity of the 3rd rocker in children who underwent TAL was lower by approximately 50–80% than that of the nonsurgical case. Furthermore, the characteristic pattern of the knee joint to foot–floor position during gait was not observed in these cases. Foot rocker analysis identified children with abnormal gait characteristics. Following surgery these gait characteristics remained abnormal.

Key words: cerebral palsy, foot rockers, tendon Achilles lengthening

1. Introduction

Cerebral palsy (CP) is a non-progressive neurological disorder caused by central nervous system damage that occurs during early development impacting the quality of a child's life. Activity limitations, such as walking, are a very common occurrence in this population. These walking limitations are associated with altered motor functions impacting both the trunk and extremities. At the level of body structure and function, very common presentations are involuntary movements, motor hyperactivity and joint contractures. A common site of contracture, in this population, is the gastrocnemius and soleus complex (the calf) contributing to abnormal foot mechanics during stance phase of gait. The contracture of the calf musculature in CP children results, in most cases, in equinus gait. This posture of the foot interferes with the first heel contact with the ground, thus disrupting controlled forward progression during stance phase. Equinus gait eliminates the normal foot mechanics describing the forward progression of the foot rockers, that is heel rocker, ankle rocker and forefoot rocker [1] (figure 1). In the case of equinus gait, the Tendon-Achilles Lengthening (TAL) surgical proce-

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dure or lengthening of the gastrocnemius aponeurosis [2], [3] is often recommended. The goal of these procedures is to provide a sufficient dorsi-flexion allowing for normal "heel to toe" progression [3]. However, if the Achilles tendon is elongated excessively, it may result in the disruption of the propulsive abilities of these plantar flexors. Therefore, the purpose of this case series is to describe the ankle and knee joint kinematics during gait with special emphasis on the modification of foot rocker during stance phase of gait in children with CP who underwent Tendon-Achilles Lengthening (TAL) procedure. We propose that the angular velocity of the foot rockers can serve as the primary criterion of functional performance during walking.

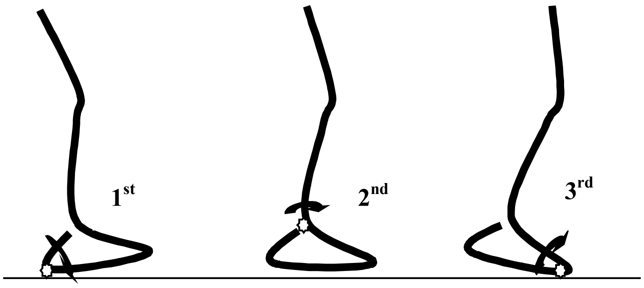

Fig. 1. Foot rockers during stance phase of gait

2. Material and method

Three children with cerebral palsy and history of TAL surgery using the Vulpius procedure [4] and one child with CP without history of surgery and good walking abilities participated in a three-year rehabilitation program with their assent and their parents' consent (table 1). The rehabilitation program was individualized and consisted of 30 to 60-minute sessions 2–4 times per week.

Gait data were recorded every 6 months using two synchronized JVC cameras at 50 Hz. In order to capture the left and right extremities, the cameras were positioned on both sides of the walkway. SIMI Reality Motion System GmbH was used for digitization of images.

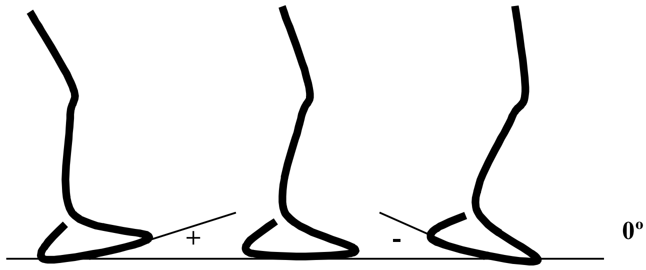

Fig. 2. Convention of the foot angle relative to the floor

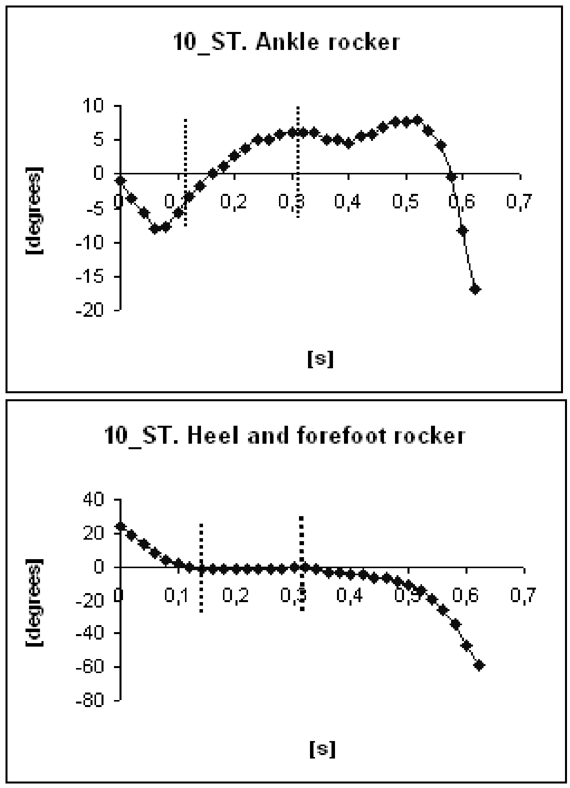

Fig. 3. Examples of the angle – time history. The heel was calculated in loading response (LR), ankle rocker in midstance (MST) and forefoot rocker in pre-swing (PSW) phase (see sections from left to right)

Table 1. Diagnosis, gait skills, GMFCS scores and timing of surgical procedures

Code & sex	Diagnosis/gait skill	GMFCS* level	TAL at age (years)	Child's age range when laboratory tests were performed
1_MJ, girl	Spastic diplegia, independent gait	III	5	7.58÷10.15
8_SA, boy	Spastic diplegia, walker and/or assistance	IV	4.1	2.21÷4.82
13_WP, boy	Spastic diplegia, walker	III	3	9.54÷12.11
10_ST, boy	Spastic hemiplegia, independent gait	I	no history of surgery	8.1÷10.69

* Gross Motor Function Classification System [6].

Anthopometric markers (1 cm in diameters) were placed at the heel, the fifth metatarsal head, ankle, knee, hip, and others, on both sides of the body. The walkway was 8 m long, allowing several ($x - y$) gait cycles to be recorded. The linear and angular kinematic analyses consisted of step and stride length as well as angular displacement of the knee, ankle and foot relative to the floor (see figure 2 for the conventions of the foot angle measurement). The velocity of the foot rockers was calculated as a mean of several (five to ten) angular positions in time. The samples of angle–time history during stance phase are presented in figure 3.

3. Results

Descriptive gait characteristics such as cadence, stance time, step length and relative step length, for all testing sessions, are presented in table 2. Boy 10_ST demonstrated good walking skills as his cadence, stance phase and step length are within normal limits [6]. Hence his gait characteristics data were used as a within study comparison with those of the remaining subjects. Gait characteristics of the other children fall below ISD norms [6]. For example, 01_MJ (girl) walks independently, but falls below the normative values for her age group. Boy (13_WP) who is unable to walk independently demonstrates prolonged stance phase and very short step length. The youngest subject (08_SA) requires moderate assistance and/or an assistive device for ambulation.

Girl 01_MJ. The first assessment was performed at the age of 7.58, which was 2.58 years following TAL. During gait, her initial contact was either with the forefoot or flatfoot. The first rocker (1.62 rad/s) was observed only during the second testing session. The second rocker was observed in sessions 01, 02 and 03 at the velocities ranging from 0.2 to 0.5 rad/s. Due to a small sample, statistical analyses of the velocities at the 1st and 2nd rockers were not performed. The third rocker was observed during all testing sessions. Velocity did not differ between left and right feet (right 2.46 (1.21) rad/s, and left 2.71 (1.60) rad/s, $t = 0.94$, $p = 0.356$). Table 3 contains average velocities of left and right feet during all six testing sessions, taking place 2.58–5.15 years after TAL.

ANOVA analysis indentified significant differences between sessions ($F = 50.01$, $p = 0.0000$). A follow-up to the t-test revealed that velocity at the third rocker was higher in session 02 than those

Table 2. Gait characteristics: cadence(f) [step/min], stance time (t) [s] and step length (L) [cm (%)]. Step length was normalized to body height

Child's code		Testing session					
		01	02	03	04	05	06
01_MJ	f	112.15	117.19	68.97	101.69	57.92	123.53
	t	0.64	0.66	0.64	0.53	1.33	0.59
	L	36 (30)	34 (28)	34 (27)	35 (28)	12 (9)	37 (28)
08_SA	f	58.7	92.02	76.74	74.71	65.78	103.45
	t	1.18	0.88	1.16	0.68	1.46	0.75
	L	21 (24)	14 (15.3)	12 (12.8)	17 (18)	12 (12.6)	26 (26)
13_WP	f	77.72	136.36	101.04	96.77	63.83	103.77
	t	0.8	0.8	0.8	0.78	1.4	0.68
	L	19 (16.8)	19 (16.1)	19 (16)	10 (8.3)	16.2 (13.1)	15 (11.7)
10_ST	f	132.36	not attended	122.95	120	125.02	129.03
	t	0.52		0.58	0.59	0.55	0.56
	L	61 (45.5)		54 (41.6)	53 (40)	61 (42)	57 (38.2)

Table 3. Angular velocity (rad/s) of the forefoot rocker for child 01_MJ. Values are mean (±SD). TAL surgery was performed at the age of 5, that is prior to the first data collection

Testing session	Age at the time of data collection (years)	Years after TAL	Angular velocity (SD) (rad/s)
01	7.58	2.58	2.64 (0.34)
02	8.2	3.20	4.39 (0.62)
03	8.68	3.68	2.49 (0.65)
04	9.19	4.19	3.76 (0.34)
05	9.67	4.67	1.01 (0.41)
06	10.15	5.15	4.01 (0.60)

in sessions 01, 03, 04 and 05 ($p < 0.05$). Similarly, velocity during session 06 was higher than those in sessions 01, 03 and 05 ($p < 0.05$).

Boy 08_SA. The first testing session was performed at the age of 2.21. There was no history of surgery at this time. He underwent TAL at the age of 4.1, before testing session 05. He weightbears on the forefoot, and accordingly only the third rocker was observed. These gait characteristics remained the same at the first test (immediately after surgery) and improved 0.72 year after surgery. Because no statistically significant difference between the right and left feet was found (right = 1.95 (0.66) rad/s, left = 2.15 (1.18) rad/s, $t = 0.89$, $p = 0.3808$), both sets of data were merged together and analyzed for intersession differences (see table 4). Statistically significant intersession difference was found by ANOVA ($F = 4.98$, $p < 0.0012$). The highest velocities of the third rocker were found in test sessions 01 (at age 2.21) and 06, (0.72 year after TAL). These differences are statistically significant when compared to the results of the remaining sessions ($p < 0.05$).

Boy 13_WP. This boy walks with an assistive device (i.e., a walker). He underwent TAL at the age of 3, and gait analyses began when he was 9.45 years old. Because of forefoot walking pattern, only the third rocker was present. No statistically significant differences between the velocities of the third rocker of the right and left leg were identified (right = 1.12 (0.75) rad/s, left = 1.52 (1.23) rad/s, $t = 1.81$, $p = 0.0829$). After combining the data for both legs at each session, between sessions differences were analyzed. A statistically significant intersession difference was identified by ANOVA ($F = 10.13$, $p < 0.0001$). The velocity of the third rocker was especially high in testing session 02, taking place 7.16 years after TAL. This velocity was different from those in the other testing sessions ($p < 0.0002$). No significant differences were found between all the sessions except for session 02 (see table 5).

Boy 10_ST. This child walks independently and efficiently. Angular velocities for all three rockers were identified, and due to no right-left asymmetry and no differences between testing sessions, his re-

Table 4. Angular velocity (rad/s) of the forefoot (3rd) rocker for child 08_SA. Values are mean (±SD). TAL surgery was performed at the age of 4.1, that is prior to testing session 05

Testing session	Age at the time of data collection (years)	Years after TAL	Angular velocity (SD) (rad/s)
01	2.21		2.59 (0.93)
02	2.82		1.83 (0.93)
03	3.31		1.51 (0.61)
04	3.82		1.69 (0.89)
05	4.30	0.20	1.78 (0.60)
06	4.82	0.72	3.00 (0.71)

Table 5. Angular velocity (rad/s) of the forefoot (3rd) rocker of child 13_WP. Values are mean (±SD). TAL surgery was performed at the age of 3, that is prior to the first testing session

Testing session	Age at the time of data collection (years)	Years after TAL	Angular velocity (SD) (rad/s)
01	9.45	6.54	1.43 (0.70)
02	10.16	7.16	3.39 (1.32)
03	10.65	7.65	1.39 (0.70)
04	11.15	8.15	0.65 (0.37)
05	11.63	8.63	0.77 (0.64)
06	12.11	9.11	1.03 (0.49)

Table 6. Angular velocity of the foot rocker (rad/s) for child 10_ST. Values are mean (±SD). There was no history of TAL surgery

Foot rocker	Angular velocity (SD) (rad/s)	CV (%)
Heel rocker (1st)	3.70 (0.71)	19.2
Ankle rocker (2nd)	0.57 (0.21)	36.8
Forefoot rocker (3rd)	6.67 (0.66)	9.9

sults were averaged rendering one angular velocity value per rocker (see table 6). The ANOVA test for intersession differences yielded $F = 0.79$, $p = 0.5628$ for the first rocker, and $F = 0.43$, $p = 0.7825$ for the third rocker. The angular velocity of the ankle joint (the 2nd rocker) was calculated only for the forward movement rendering a velocity of 0.57 (0.21) rad/s. The coefficient of variability (CV) for the angular velocity of the second rocker was 36.8% as compared to 19.2% and 9.9% of the first and third rockers.

4. Discussion and summary

Over 60% of young children suffering from CP are toe-walkers [7]. The equinovarus foot deformity, associated with toe walking, affects about 44% of children with diplegia [8].

A common procedure for equinovarus foot deformity is TAL. The goal of that procedure is to lengthen the gastrocnemius-soleus complex with the aim of restoring functional gait. The success rate of such surgeries is not always satisfactory as they often result in an over-elongation of the plantar-flexor complex, contributing to a flat-foot gait. The flat-foot gait lacks the first (heel) rocker. The recurrence of this gaastroc-soleus contracture is less frequent in children with diplegia [9] than in those who took part in this investigation.

All three rockers were present in child 10_ST. His overall movement impairment was low (GMFCS level I), and he did not undergo the TAL surgery. His gait kinematics were within normative values established for similar age healthy children [3]. Therefore, his gait characteristics were used as a reference for the other children in this study. Angular velocities of the first (3.70 rad/s) and second (0.57 rad/s) rockers were, on average, 45 and 92% respectively lower than the velocity of the third rocker, which amounted to 6.67 rad/s. Children with history of TAL surgery, having almost no indication of the first and second rockers, clearly show lower velocities of the third rocker (i.e., 50–80% less than 10_ST). The contracture of gastrocnemius-soleus complex influences the relative movement of the foot and knee in the stance phase of gait (figure 4). The normal pattern (see boy

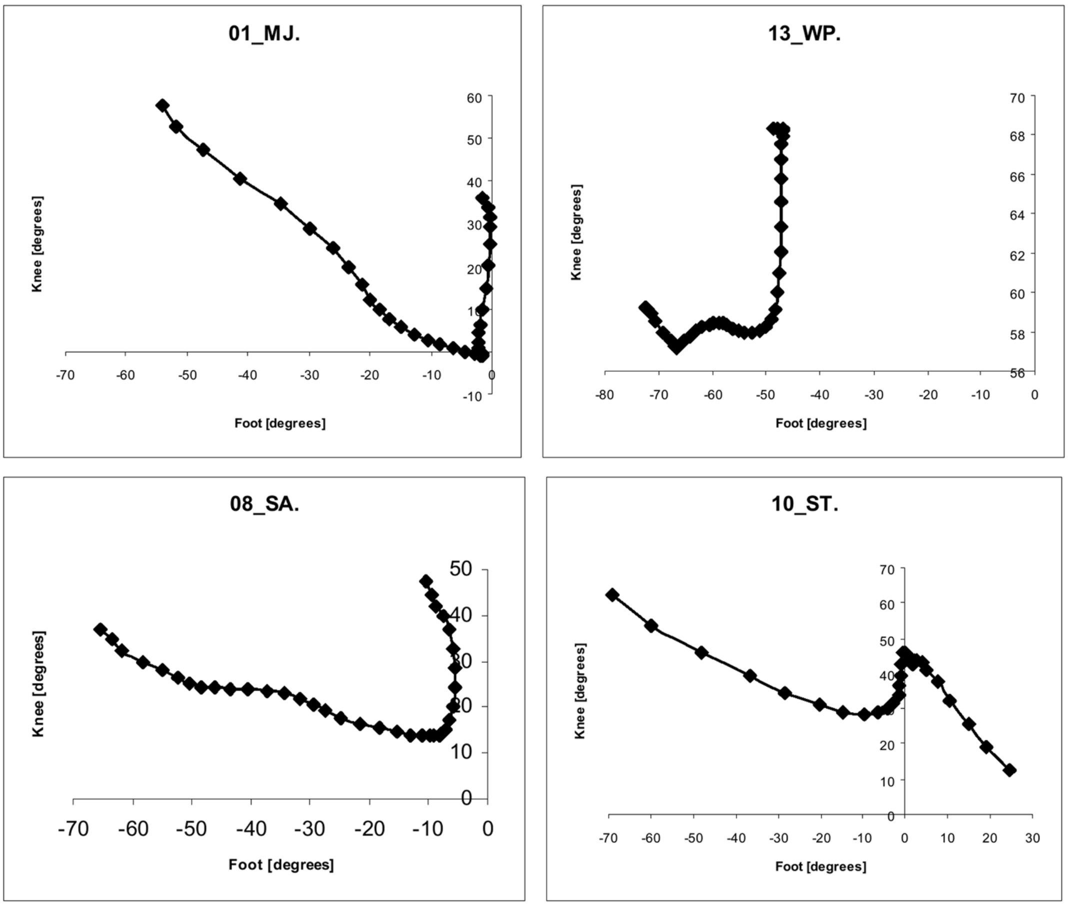

Fig. 4. Knee-foot angle in stance phase of the four children

10_ST) is characterized by a decreased foot–ground angle with simultaneous knee flexion in loading response. This pattern was not observed in the remaining three cases who were more or less habitual toe walkers [10]. Girl 01_MJ exhibits a foot-flat at an initial contact while simultaneously extending the knee. This past-retract event allows the child to gain stability by "locking" the knee. Even more clearly, this angle–angle relationship with forefoot support is seen in boy 08_SA. A distinctly different presentation of the foot angle–knee angle relationship is seen in boy 13_WP (level IV GMFCS), where angular movement in forefoot is limited by the knee. This is a typical example of crouch gait, where the forefoot support is maintained for a long time and this is accompanied by a small change of knee angle. This stiff knee provides a weaker propulsion. Crouch gait is typical of older children with the history of CP, with or without the history of TAL. Based on the relative angular position in these joints a constant length of the gastrocnemius muscle as a two-joint may be expected. This boy underwent the TAL surgery at the age of 3 years, i.e., 6.54 years before the current investigation. The calf muscle contracture (child 13_WP) may be a result of alteration in the central nervous system and improper choice of surgical intervention. These observations may be in contrast to the results described by ENGSBERG [3], who suggests a genetic tendency of connective tissue to scar, and/or negligence in rehabilitation.

Subjective observations and minimally increased velocity of the third rocker and better angular pattern of the foot in the last (06) testing session, i.e., half a year after the surgery, suggest a promising result of surgical intervention and rehabilitation in boy 8_SA. However, as for the two other children who underwent the TAL intervention, no progress in the function of the knee and the foot was found during the 3-year-long rehabilitation program.

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