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Kinematic and kinetic factors that correlate with improved knee flexion following treatment for stiff-knee gait

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Abstract

Stiff-knee gait is a movement abnormality in which knee flexion during swing phase is significantly diminished. This study investigates the relationships between knee flexion velocity at toe-off, joint moments during swing phase and double support, and improvements in stiff-knee gait following rectus femoris transfer surgery in subjects with cerebral palsy. Forty subjects who underwent a rectus femoris transfer were categorized as "stiff" or "not-stiff" preoperatively based on kinematic measures of knee motion during walking. Subjects classified as stiff were further categorized as having "good" or "poor" outcomes based on whether their swing-phase knee flexion improved substantially after surgery. We hypothesized that subjects with stiff-knee gait would exhibit abnormal joint moments in swing phase and/or diminished knee flexion velocity at toe-off, and that subjects with diminished knee flexion velocity at toe-off would exhibit abnormal joint moments during double support. We further hypothesized that subjects classified as having a good outcome would exhibit postoperative improvements in these factors. Subjects classified as stiff tended to exhibit abnormally low knee flexion velocities at toe-off ($p<0.001$) and excessive knee extension moments during double support ($p = 0.001$). Subjects in the good outcome group on average showed substantial improvement in these factors postoperatively. All eight subjects in this group walked with normal knee flexion velocity at toe-off postoperatively and only two walked with excessive knee extension moments in double support. By contrast, all 10 of the poor outcome subjects walked with low knee flexion velocity at toe-off postoperatively and seven walked with excessive knee extension moments in double support. Our analyses suggest that improvements in stiff-knee gait are associated with sufficient increases in knee flexion velocity at toe-off and corresponding decreases in excessive knee extension moments during double support. Therefore, while stiff-knee gait manifests during the swing phase of the gait cycle, it may be caused by abnormal muscle activity during stance.

Keywords: Cerebral palsy; Stiff-knee gait; Rectus femoris transfer; Double support

1. Introduction

Many persons with cerebral palsy walk with a stiff-knee gait in which swing-phase knee flexion is significantly diminished and delayed. This gait pattern inhibits toe clearance and can result in tripping or require energy-inefficient compensatory movements (Sutherland and Davids, 1993). Stiff-knee gait is thought to be

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caused primarily by inappropriate activity of the rectus femoris muscle during swing phase (Perry, 1987; Sutherland et al., 1990; Waters et al., 1979), resulting in excessive swing-phase knee extension moments. Accordingly, stiff-knee gait is often treated with a rectus femoris transfer (Gage et al., 1987; Perry, 1987), in which the insertion of this muscle is relocated to a site that decreases its ability to generate a knee extension moment. Unfortunately, outcomes of the rectus femoris transfer procedure are inconsistent; some subjects show substantial improvement in their swing-phase knee flexion postoperatively, but others show little change.

There is some uncertainty as to whether excessive swing-phase knee extension moments are the dominant cause of stiff-knee gait. Computer simulation of stiff-knee gait in individuals following stroke has shown that increasing the swing-phase hip flexion moment can significantly increase the range of motion of the knee (Kerrigan et al., 1998). However, Goldberg et al. (2003) observed that many stiff-knee subjects with cerebral palsy do not exhibit diminished hip flexion moments or excessive knee extension moments during swing phase, but instead walk with a low knee flexion velocity at toe-off. These authors showed that a simulated increase in subjects' knee flexion velocity at toe-off resulted in an increased range of knee flexion in swing, suggesting that interventions that increase this velocity have the potential to improve peak knee flexion during swing. More recently, analyses based on simulations of normal gait have demonstrated that diminished force during double support in either iliopsoas or gastrocnemius and excessive force during double support in either vasti or rectus femoris have the potential to decrease knee flexion velocity at toe-off (Goldberg et al., 2004).

To evaluate the relevance of these variables to stiff-knee gait and its treatment, we generated three hypotheses regarding the kinematic and kinetic factors that contribute to stiff-knee gait in subjects with cerebral palsy. First, we hypothesized that subjects with stiff-knee gait would exhibit one or more of three potential causes of diminished knee flexion in swing phase: excessive knee extension moments in swing phase, diminished hip flexion moments in swing phase, or diminished knee flexion velocity at toe-off. Second, we hypothesized that subjects with low knee flexion velocity at toe-off would exhibit excessive knee extension moments during double support and/or diminished hip flexion moments during double support. Finally, we hypothesized that postoperative improvement in those factors that contribute to stiff-knee gait would correlate with improved swing-phase knee kinematics. We tested these hypotheses by examining the moments during double support, moments during swing phase, and knee flexion velocity at toe-off before and after surgery for a group of subjects with cerebral palsy who all received a rectus femoris transfer.

2. Materials and methods

The subjects in this study underwent gait analysis at Connecticut Children's Medical Center in Hartford, CT, as part of the routine treatment-planning process. The inclusion criteria for this study required that each subject (i) underwent rectus femoris transfer surgery in an effort to correct or prevent stiff-knee gait, (ii) was between the ages of 6 and 17 before surgery, (iii) had not undergone a selective dorsal rhizotomy, and (iv) did not require orthoses or other assistance to walk. A total of 40 subjects were identified who met these criteria. Control data were collected in the same laboratory from 15 able-bodied subjects of approximately the same average age, height, and weight as the subjects with cerebral palsy (Table 1). All subjects gave informed consent for the collection of their gait data. Retrospective analysis of these data was performed in accordance with the regulations of the participating institutions.

All subjects underwent a routine clinical exam and gait analysis, including three-dimensional kinematic and kinetic analyses and preoperative collection of surface electromyographic recordings from selected muscles. Motion data were collected using a multiple-camera motion measurement system, and each subject's gait kinematics and kinetics were computed using methods described by Davis et al. (1991). Joint moments were normalized by subject weight.

Each limb that had undergone a rectus femoris transfer in the group of 40 subjects with cerebral palsy was categorized based on whether the preoperative kinematics exhibited a stiff-knee gait pattern. Four gait parameters (Fig. 1) were selected as measures of whether a subject walked with stiff-knee gait: peak knee flexion in swing phase (e.g., Gage et al., 1987; Sutherland et al., 1990), knee range of motion in early swing phase measured from toe-off to peak flexion (Goldberg et al., 2003), total knee range of motion during gait (e.g., Gage et al., 1987; Õunpuu et al., 1993), and timing of peak knee flexion during swing phase (e.g., Sutherland et al., 1990; Õunpuu et al., 1993). The average value of each parameter for the able-bodied subjects was also determined. For each subject with cerebral palsy, a measure was characterized as indicative of stiff-knee gait if it was more than two standard deviations below the average normal value, or, in the case of the timing measure, more than two standard deviations above the average normal value (Table 1). A limb was classified as "stiff" if three or more of these measures were indicative of stiff-knee gait. A limb was classified as "not-stiff" if one or none of these measures was indicative of stiff-knee gait. If two of the measures were indicative of stiff-knee gait, the limb was classified as a borderline case and was excluded. In subjects for whom both limbs met the stiff criterion, the limb that was more stiff was included. If

Table 1
Descriptive average values for the able-bodied subjects, the not-stiff and stiff subjects with cerebral palsy, and the good and poor outcome subjects preoperatively and postoperatively

	Able-bodied			Stiff			
		Cerebral palsy		Good outcome		Poor outcome	
		Not-stiff	Stiff	Pre	Post	Pre	Post
Number of subjects	15	10	23	8	—	10	—
Male/female	7M/8F	3M/7F	18M/5F	5M/3F	—	8M/2F	—
Hemiplegic/diplegic	—	5H/5D	6H/17D	4H/4D	—	0H/10D	—
Age (years)	10 (2.8)	12	11	11	12[a]	11	13[a]
Height (cm)	138 (18.2)	143	137	135	143[a]	137	145[a]
Weight (kg)	34 (13.4)	37	33	29	33[a]	35	40[a]
Walking speed (cm/s)	120 (13.6)	116	**103**	110	110	**100**	**97**
Measures of stiff-knee gait							
Knee ROM from toe-off to peak flexion (°)	31 (4.3)	26	**14**[a]	**17**	27[a]	**12**	**12**[b]
Knee ROM total (°)	60 (6.8)	**53**	**30**[a]	**35**	55[a]	**28**	**33**[b]
Peak knee flexion in swing (°)	66 (5.3)	61	**48**[a]	**47**	**60**[a]	**47**	**45**[b]
Timing of peak knee flexion (% swing)	33 (3.1)	36	**45**[a]	**40**	36	**47**	35[a]

Able-bodied subject values are given as average (standard deviation).
Bold indicates that *t*-test showed value to be statistically different from normal, $p < 0.05$.
[a] *t*-test indicates that not-stiff/stiff or pre/post values are statistically different from each other $p < 0.05$.
[b] Paired *t*-test indicates that good/poor outcome values are statistically different from each other, $p < 0.05$.

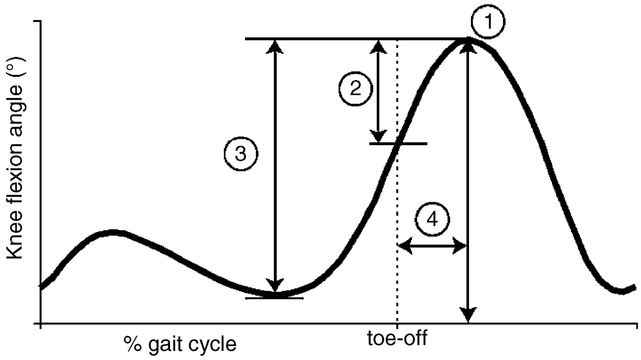

Fig. 1. The four gait parameters selected as measures of whether a subject walked with a stiff-knee gait: (1) peak knee flexion angle, (2) range of knee flexion in early swing measured from toe-off to peak flexion, (3) total range of knee motion, and (4) timing of peak knee flexion in swing. A measure was indicative of stiff-knee gait if the value was more than two standard deviations below the average normal value in the case of measures 1–3, or more than two standard deviations above the average normal value in the case of measure 4. A limb was considered "stiff" if three or more of the measures were indicative of stiff-knee gait. A limb was considered "not-stiff" if one or none of the measures were indicative of stiff-knee gait. If two of the measures were indicative of stiff-knee gait, the limb was classified as a borderline case and was excluded.

both limbs met the not-stiff criterion, one limb was chosen at random. Ten subjects met the not-stiff criterion and 23 met the stiff criterion.

The group of 23 subjects who were classified as stiff preoperatively was further divided into groups based on whether their postoperative kinematics exhibited a stiff-knee gait pattern. Subjects were categorized as exhibiting a "good outcome" if postoperatively their limb was classified as not-stiff, and subjects were categorized as exhibiting a "poor outcome" if postoperatively their limb was still classified as stiff (Table 1 and Fig. 2). Subjects were excluded from further analysis if postoperatively their limb was classified as a borderline case or if their postoperative gait data were unavailable. Ten subjects met the good outcome criterion and eight met the poor outcome criterion. There were no significant differences in the average age, height, weight, or walking speed of the two groups (Table 1). All 18 subjects had at least one concomitant surgical procedure in addition to the rectus femoris transfer, including hamstring lengthening (18 subjects), gracilis lengthening or tenotomy (10), gastrocnemius and/or soleus lengthening (12), de-rotational osteotomy (6), and/or foot surgery (4). There were no consistent differences in the concomitant procedures performed on subjects in the good and poor outcome groups. More information about each subject, including their surgical treatment, is available as supplementary material at doi:10.1016/j.jbiomech.2005.01.015.

For each subject, hip and knee joint moments were each calculated and averaged during the periods of both double support and early swing phase. Double support was defined as the period between contralateral foot contact and ipsilateral toe-off. Early swing phase was defined as the period between toe-off and peak knee flexion. Toe-off was defined as when the ground reaction force dropped below 5% of body weight.

We evaluated our first two hypotheses by conducting one-tailed Fisher exact tests. For our first hypothesis, we

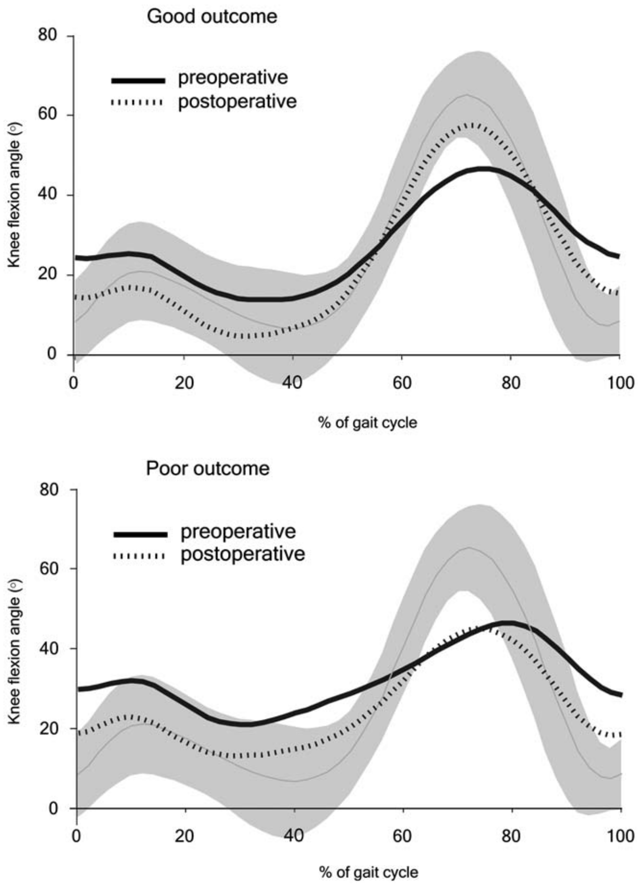

Fig. 2. Average knee flexion preoperatively and postoperatively for (a) the good outcome group and (b) the poor outcome group. Normal knee flexion is shown as a thin gray line, and two standard deviations of the normal curve are indicated by the shaded region. For both groups, the preoperative average values of each of the four measures of stiff-knee gait were significantly different from normal ($p<0.05$, Table 1). Postoperatively, the poor outcome group showed improvement only in the timing of peak knee flexion in swing, while the good outcome group showed significant improvement in all other measures ($p<0.05$, Table 1).

cross-classified the subjects with cerebral palsy in 2×2 contingency tables based on whether a subject exhibited stiff-knee gait and whether the subject exhibited excessive knee extension moments in swing phase, diminished hip flexion moments in swing phase, or low knee flexion velocity at toe-off. For our second hypothesis, we cross-classified the subjects in additional 2×2 contingency tables based on whether a subject walked with low knee flexion velocity at toe-off and whether the subject exhibited diminished hip flexion moments or excessive knee extension moments during double support. Our goal was to assess (i) whether the subjects classified as stiff would be more likely than those who were classified as not-stiff to exhibit the three potential causes of stiff-knee gait, and (ii) whether the subjects who walked with low knee flexion velocity at toe-off would be more likely than those who did not to exhibit abnormal hip or knee moments during double support. In our analysis, a value was considered to be abnormal if it deviated from the mean value for the able-bodied subjects by more than two standard deviations.

Table 2
Association between stiff-knee gait and low knee flexion velocity at toe-off in subjects with cerebral palsy

	Not stiff	Stiff
Knee flexion velocity at toe-off in normal range	9	4
Knee flexion velocity at toe-off below normal	1	19

Fisher exact test showed that the association is significant, $p<0.001$.

Our third hypothesis was evaluated by comparing average values of interest for the good outcome, poor outcome, and able-bodied groups using analysis of variance and *t*-tests with a Holm correction for multiple comparisons. Paired *t*-tests were used to test for differences between the pre- and postoperative conditions within the good and poor outcome groups. The kinematic and kinetic factors associated with improved swing-phase knee flexion were identified. In all cases, $p<0.05$ indicated significance.

3. Results

Subjects who walked with stiff-knee gait tended to walk with low knee flexion velocity at toe-off, while those who did not walk with stiff-knee gait tended to walk with a normal knee flexion velocity at toe-off ($p<0.001$, Table 2). Nineteen of the 23 subjects classified as stiff exhibited an abnormally low knee flexion velocity at toe-off. Further, knee flexion velocity at toe-off was found to correlate with early swing-phase knee range of motion ($R^2 = 0.56$, Fig. 3a). No subject with stiff-knee gait walked with a diminished average hip flexion moment or an excessive average knee extension moment during swing phase, and neither the swing-phase hip moment nor the swing-phase knee moment was correlated with early swing-phase knee range of motion (Fig. 3b and c).

Subjects who walked with low knee flexion velocity at toe-off tended to exhibit excessive knee extension moments in double support, while subjects who walked with normal knee flexion velocity at toe-off tended to exhibit knee extension moments in double support that were normal or below normal ($p = 0.001$, Table 3). This trend is supported by the observation that the average knee extension moment during double support was correlated with knee flexion velocity at toe-off ($R^2 = 0.54$, Fig. 4a). No subject walked with diminished average hip flexion moments in double support, nor was

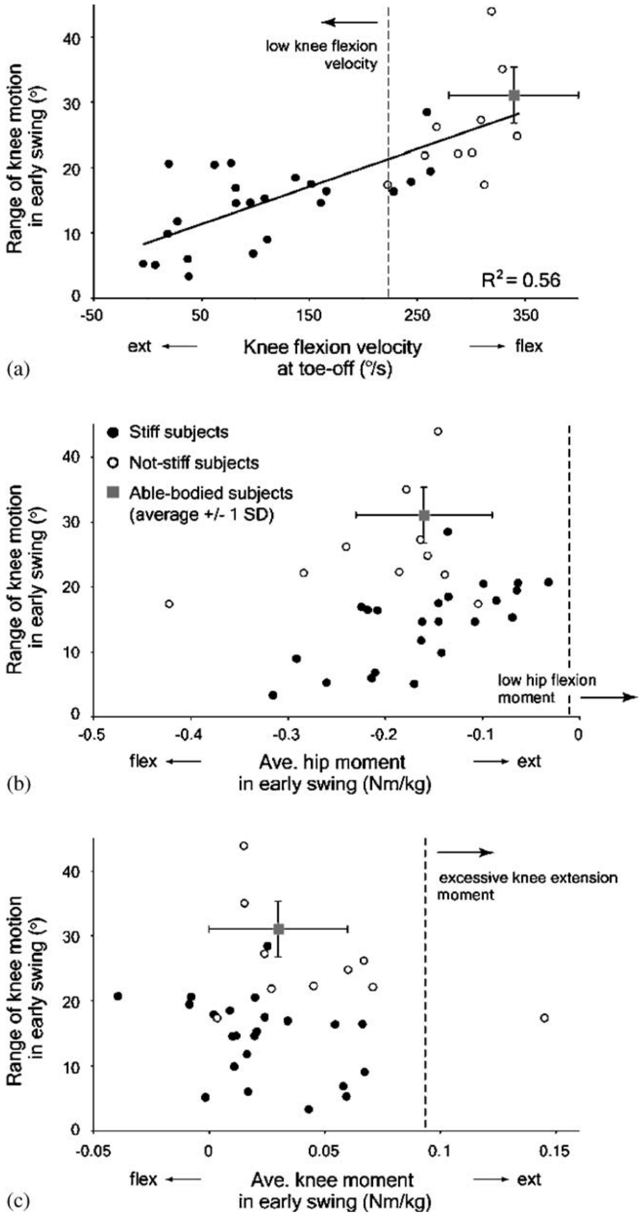

Fig. 3. Range of knee flexion in early swing phase as measured from toe-off to peak knee flexion for the subjects with cerebral palsy, plotted versus (a) knee flexion velocity at toe-off, (b) average hip flexion moment in early swing phase, (c) average knee extension moment in early swing phase. The average values for the able-bodied subjects are also plotted, with error bars showing one standard deviation. Dotted lines show two standard deviations from normal, indicating the criterion for determining whether a value was abnormal. The linear relationship between knee flexion velocity at toe-off and range of knee flexion in early swing phase is indicated by the solid line. No stiff-knee subjects exhibited a low hip flexion moment or an excessive knee extension moment.

this variable correlated with knee flexion velocity at toe-off (Fig. 4b).

Increases in knee flexion velocity at toe-off were associated with improvements in stiff-knee gait. In the good outcome group, six of the eight subjects walked with low knee flexion velocity at toe-off preoperatively (Fig. 5a). Postoperatively, all eight subjects exhibited a knee flexion velocity at toe-off in the normal range (Fig. 5a). The average knee flexion velocity at toe-off for this group was below normal preoperatively, but increased to a value in the normal range postoperatively ($p < 0.05$, Table 4). In the poor outcome group, 8 of the 10 subjects walked with low knee flexion velocity preopera-

Table 3
Association between low knee flexion velocity at toe-off and excessive knee extension moments in double support in subjects with cerebral palsy

	Normal knee flexion velocity at toe-off	Low knee flexion velocity at toe-off
Knee moment in double support normal or below normal	10	3
Knee moment in double support above normal	3	17

Fisher exact test showed that the association is significant, $p = 0.001$.

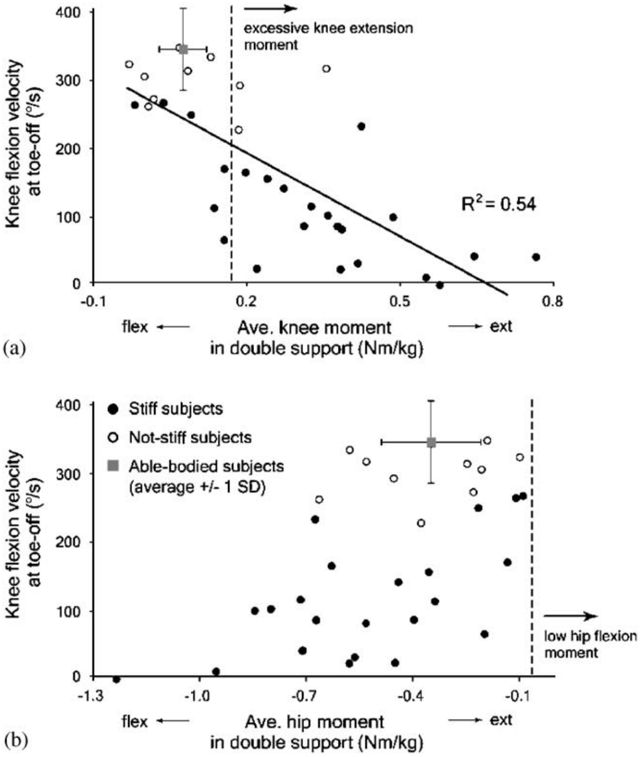

Fig. 4. Knee flexion velocity at toe-off for the subjects with cerebral palsy, plotted versus (a) average knee moment in double support and (b) average hip moment in double support. The average values for the able-bodied subjects are also plotted, with error bars showing one standard deviation. Dotted lines show two standard deviations from normal, indicating the criterion for determining whether a value was abnormal. The linear relationship between average knee extension moments in double support and knee flexion velocity at toe-off is indicated by the solid line.

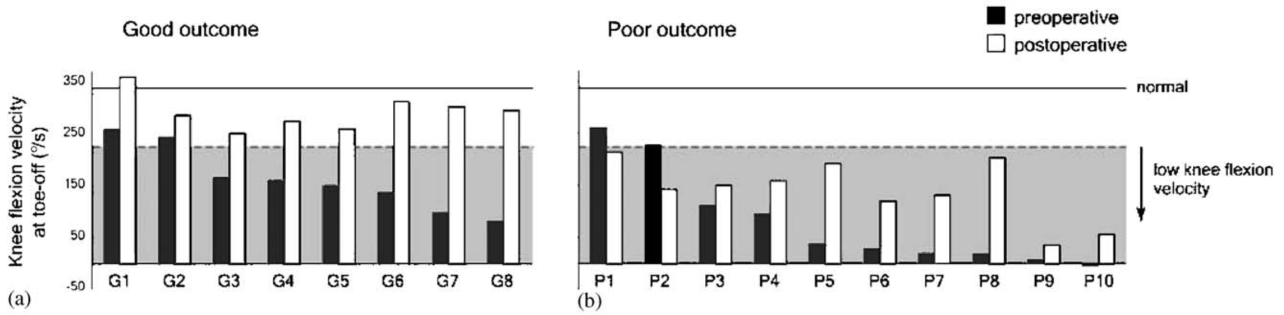

Fig. 5. Pre- and postoperative knee flexion velocity at toe-off for subjects in the (a) good outcome and (b) poor outcome groups. The average knee flexion velocity at toe-off for the able-bodied individuals is indicated by the solid line. Velocities that were more than two standard deviations below the average normal value were classified as low, indicated by the shaded region. Postoperatively, all subjects in the good outcome group walked with knee flexion velocities at toe-off in the normal range, while all subjects in the poor outcome group walked with knee flexion velocities at toe-off that were low.

Table 4
Descriptive average values for the able-bodied group and the good outcome and poor outcome subjects preoperatively and postoperatively

	Able-bodied[a]	Stiff			
		Good outcome		Poor outcome	
		Pre	Post	Pre	Post
Contributors to peak knee flexion in swing					
Knee flexion velocity at toe-off (°/s)	340 (60)	**160**	295[c]	**80**[d]	**140**[c,d]
Ave. hip moment[b] in early swing (Nm/kg)	−0.164 (0.070)	−0.15	−0.16	−0.17	−0.20
Ave. knee moment[b] in early swing (Nm/kg)	0.034 (0.028)	0.03	0.03	0.02	0.04[c]
Contributors to knee flexion velocity at toe-off					
Ave. hip moment[b] in double support (Nm/kg)	−0.347 (0.137)	−0.38	−0.33	**−0.68**	**−0.51**[c,d]
Ave. knee moment[b] in double support (Nm/kg)	0.076 (0.046)	**0.20**	0.05[c]	**0.42**[d]	**0.26**[c,d]

Bold indicates that *t*-test showed value to be statistically different from normal, $p < 0.05$.

[a] Able-bodied subject values are given as average (standard deviation).

[b] Extension moment is positive.

[c] *t*-test indicates that pre/post outcome values are statistically different from each other, $p < 0.05$.

[d] Paired *t*-test indicates that good/poor outcome values are statistically different from each other, $p < 0.05$.

tively, and all 10 subjects did so postoperatively (Fig. 5b). While the average knee flexion velocity at toe-off for this group increased postoperatively, it was significantly below normal both before and after surgery ($p < 0.05$, Table 4).

Decreases in the average knee extension moment in double support were associated with improvements in stiff-knee gait. In the good outcome group, five of the eight subjects walked with excessive knee extension moments in double support preoperatively, while only two did so postoperatively (Fig. 6a). The average knee extension moment in double support for this group was above normal preoperatively, but decreased to a value in the normal range postoperatively ($p < 0.05$, Table 4; see also data for Subject G7 in Fig. 7c). In the poor outcome group, 9 of the 10 subjects walked with excessive knee extension moments in double support preoperatively and seven still did so postoperatively (Fig. 6b). While the average knee extension moment in double support for this group decreased postoperatively, it was significantly above normal both before and after surgery ($p < 0.05$, Table 4; see also data for Subject P9 in Fig. 8c).

4. Discussion

Stiff-knee gait may be caused by multiple factors, but is primarily thought to result from excessive knee extension moments during swing phase. Accordingly, improvement in stiff-knee gait following transfer of the rectus femoris is often attributed to a reduction in these swing-phase moments. However, none of the subjects who demonstrated favorable outcomes in this study exhibited excessive knee extension moments during swing phase preoperatively, nor did these subjects show a consistent decrease in these moments postoperatively. Instead, most subjects with favorable outcomes exhibited a substantial increase in their abnormally low knee flexion velocity at toe-off and a corresponding decrease

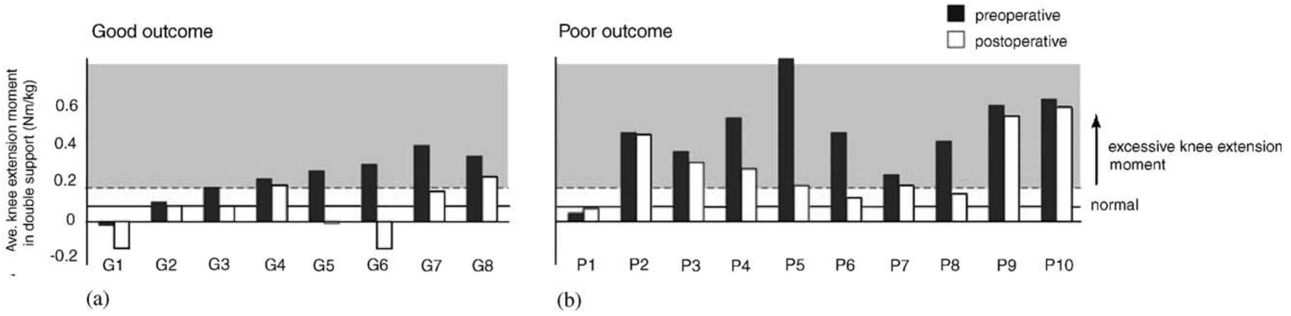

Fig. 6. Pre- and postoperative knee extension moments, averaged over the period of double support, for subjects in the (a) good outcome and (b) poor outcome groups. The average knee extension moment in double support for the able-bodied individuals is indicated by the solid line. Knee extension moments that were more than two standard deviations above the average normal value were classified as excessive, indicated by the shaded region. Postoperatively, most subjects in the good outcome group walked with average knee extension moments in the normal range, while most subjects in the poor outcome group walked with excessive knee extension moments in double support.

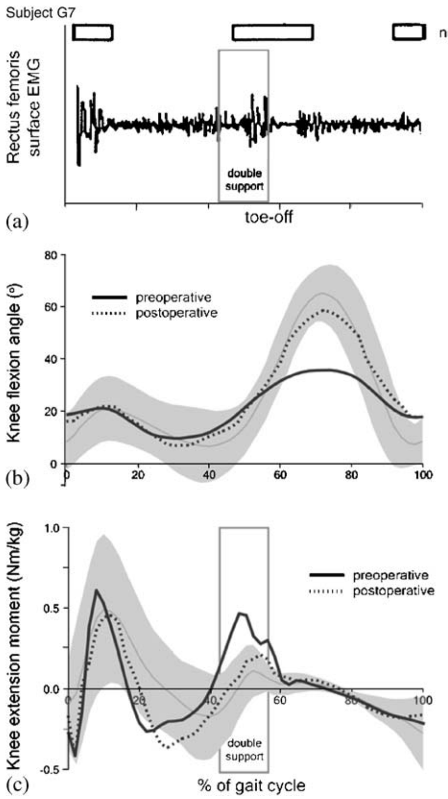

Fig. 7. Gait data for a subject in the good outcome group showing (a) preoperative EMG activity of rectus femoris, (b) pre- and postoperative knee flexion angle, and (c) pre- and postoperative knee extension moment. The average knee angles and moments for the able-bodied individuals are shown as thin gray lines, and two standard deviations of the normal curves are indicated by the shaded regions. Normal rectus femoris EMG timing is indicated by horizontal white bars (Bleck, 1987). The period of double support for this subject is shown on the EMG and moment plots as an outlined vertical region. Additional information about this subject is available as supplementary material at doi:10.1016/j.jbiomech.2005.01.015.

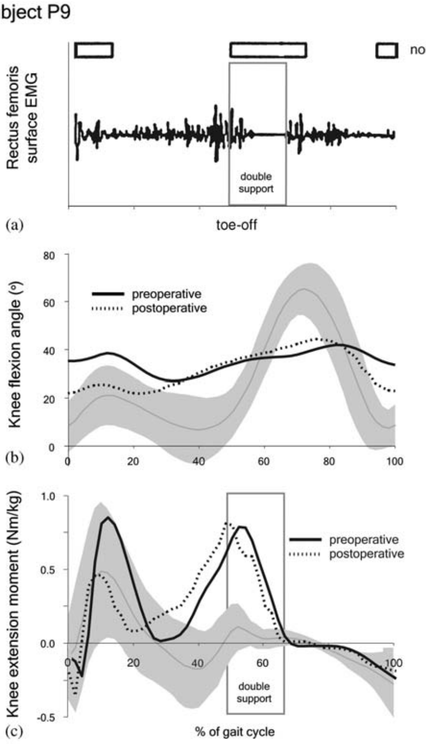

Fig. 8. Gait data for a subject in the poor outcome group showing (a) preoperative EMG activity of rectus femoris, (b) pre- and postoperative knee flexion angle, and (c) pre- and postoperative knee extension moment. The average knee angles and moments for the able-bodied individuals are shown as thin gray lines, and two standard deviations of the normal curves are indicated by the shaded regions. Normal rectus femoris EMG timing is indicated by horizontal white bars (Bleck, 1987). The period of double support for this subject is shown on the EMG and moment plots as an outlined vertical region. Additional information about this subject is available as supplementary material at doi:10.1016/j.jbiomech.2005.01.015.

in their abnormally high knee extension moment during double support (Figs. 5a and 6a).

Subjects in this study underwent multiple concomitant treatments, and it is possible that multiple treatments affected the subjects' knee motions during walking. However, since all of the subjects underwent a rectus femoris transfer, and since this was the only procedure intended to alter the subjects' swing-phase knee flexion, it is fitting to consider the role that the transfer may have played in our findings. Excessive knee extension moments during double support could have been due, in part, to excessive force in rectus femoris during this period. All of the subjects in our good and poor outcome groups demonstrated some rectus femoris activity during double support preoperatively (e.g., Figs. 7a and 8a), suggesting that the transfer procedure had the potential to diminish the subjects' knee extension moments in double support. It follows that for subjects in the good outcome group, the transfer procedure may have improved knee flexion in swing due to its effect on rectus femoris function in stance. Indeed, Hadley et al. (1992) and Õunpuu et al. (1993, in Fig. 1) have shown that knee flexion velocity at toe-off often increases in subjects with cerebral palsy following a rectus femoris transfer in combination with other treatments. Our conclusion is further supported by the finding that for stroke subjects with stiff-knee gait, improved outcomes resulted from surgical alteration of quadriceps muscles that were active in pre-swing (Waters et al., 1979).

There are several possible reasons why subjects in the poor outcome group did not show more improvement postoperatively. First, the poor outcome group on average walked with more stance-phase knee flexion than the good outcome group, both before and after surgery (Fig. 2). Gage et al. (1987) made a similar observation, finding that in a group of subjects with cerebral palsy who had rectus femoris transfers, the 10 worst results had more residual knee flexion in stance postoperatively than the 10 best results. For subjects who walked with this crouched gait postoperatively, rectus femoris activity may have been required during double support to maintain this posture, contributing to the diminished swing-phase knee flexion of these subjects. Second, it is possible that the rectus femoris surgery could not adequately compensate for the severity of the gait deviations of the poor outcome subjects. In our study, the poor outcome group on average had larger knee extension moments during double support and lower knee flexion velocities at toe-off preoperatively than the subjects in the good outcome group (Table 4). While this may, in part, be due to the more crouched postures of these subjects, this finding suggests that there may be a limit to the improvement that can be expected in the surgical treatment of stiff-knee gait. Third, the rectus femoris transfer may have been ineffective for some subjects due to surgical complications. Asakawa et al. (2004) have observed the presence of scar tissue between the transferred rectus femoris and the underlying vasti that could limit the ability of the rectus femoris to transmit force independently from the vasti.

It is also possible that in the poor outcome group there were factors contributing to the subjects' excessive knee extension moments during double support that were not addressed by the rectus femoris transfer. Specifically, excessive knee extension moments could have been due to vasti activity during double support, which we observed in some subjects and which has been shown to limit the success of surgical treatment of stiff-knee gait (Kerrigan et al., 1991; Waters et al., 1979). Also, many of the subjects had weak plantarflexors. If the knee flexion moment generated by gastrocnemius was diminished for these subjects, this could have contributed to an excessive knee extension moment in double support and diminished knee flexion velocity at toe-off (Goldberg et al., 2004).

Other studies have found correlations between clinical measures and outcomes following the rectus femoris transfer that we did not observe. Gage et al. (1987) noted that postoperatively subjects who had the worst outcomes also exhibited excessive foot rotation, either internal or external. However, we found that more than half of the subjects in both the good and poor outcome groups exhibited excessive foot rotation ($>10^\circ$ internal or external from normal) postoperatively. Kay et al. (2004) found that subjects who had a positive score on the Duncan Ely test for rectus femoris spasticity showed more improvement in postoperative range of motion at the knee than those with a negative score. This correlation was not observed in our study, as most subjects in both our good and poor outcome groups had a positive score on the Ely test preoperatively.

Knee kinematics and kinetics change with walking speed (van der Linden et al., 2002; Winter, 1991). Most subjects in our study did not walk substantially slower than normal (see Table S1 at doi:10.1016/j.jbiomech.2005.01.015). Nonetheless, to assess how walking speed may have affected our findings, we estimated speed-matched normal values for all of the parameters measured in this study by fitting curves to the pediatric knee kinematic and kinetic data reported by van der Linden et al. (2002) as a function of walking speed. We then shifted each curve-fit such that it passed through our average normal value at our average normal walking speed and used these curves to calculate speed-appropriate normal values for each subject. Taking walking speed into account, some subjects no longer met our rigorous criteria of "stiff" preoperatively. However, re-categorizing the subjects in Tables 2 and 3 after accounting for walking speed did not significantly affect these results, as, in general, the subjects' knee flexion velocities at toe-off were sufficiently low such that the decrease could not be attributed to walking speed alone. Specifically, using speed-matched average normal values for each subject, 19 of the 23 subjects classified as stiff still walked with a low knee flexion velocity at toe-off, none exhibited diminished hip flexion moments in swing phase, and only one exhibited an excessive knee extension moment in swing. When walking speed was taken into account, two subjects in the poor outcome group were classified as not-stiff postoperatively. Therefore, in these two cases, the "poor outcome" may have been due to a postoperative decrease in walking speed. It remains unclear whether stiff-knee gait is in some cases simply a consequence of slow walking, or whether some subjects walk slowly because they cannot flex their knees adequately.

We had expected to find evidence that different factors contribute to stiff-knee gait in different subjects. The fact that excessive knee extension moments in double support and low knee flexion velocity at toe-off were found to be the predominant contributors may be a result of our subject inclusion criteria (i.e. our exclusion of borderline cases) and our definition of deviation from normal. For example, had we chosen one standard deviation as our criterion for determining whether a moment was outside of the normal range, four stiff subjects would have exhibited excessive swing-phase knee extension moments and five would have exhibited diminished swing-phase hip flexion moments. Swing-phase moments, particularly at the knee, are relatively small, are difficult to measure accurately, and show wide variation even in normal gait. It is possible that deviations in these moments that are smaller than our ability to accurately measure could account for diminished swing-phase knee flexion in some cases.

We had hypothesized that some subjects with stiff-knee gait would exhibit diminished hip flexion moments in double support, but we did not observe this. Had we used the less stringent one standard deviation from normal criterion, four stiff subjects would have exhibited diminished hip flexion moments in double support. Surprisingly, we found that many stiff subjects, particularly in the poor outcome group, exhibited excessive hip flexion moments during double support (Table 4 and Fig. 4b). This may have been related to excessive activity in the bi-articular rectus femoris, or to a delay in the peak hip flexion moment of these subjects, which often occurred during double support as opposed to before double support as observed in our able-bodied subjects.

The ankle plantarflexion moment in late stance is generally thought to contribute to the initiation of swing-phase (Hof et al., 1993; Meinders et al., 1998; Neptune et al., 2001; Perry, 1992; Winter and Eng, 1983). In our analysis of the contributors to low knee flexion velocity at toe-off, we chose to report hip and knee moments during double support and not the ankle plantarflexion moment. We made this choice because a low ankle plantarflexion moment could be indicative of diminished force in soleus and/or gastrocnemius, and these muscles have been shown to make opposite contributions to knee flexion velocity at toe-off. Goldberg et al. (2004) showed that in a simulation of normal gait, decreased force in soleus during double support increased knee flexion velocity at toe-off, while decreased force in gastrocnemius decreased this velocity. Therefore, a decreased ankle plantarflexion moment is only an indicator of a decreased contribution to knee flexion velocity at toe-off if it represents diminished force in gastrocnemius. Since the bi-articular gastrocnemius also generates a knee moment, we believe that our analysis of knee moments in double support accounts for the potential influence of this muscle. Further, while most of the subjects in this study walked with diminished average ankle plantarflexion moments during double support, we did not find this value to correlate with knee flexion velocity at toe-off. To more thoroughly elucidate the role of the plantarflexors in stiff-knee gait, an analysis that can account for individual muscles is needed.

This study revealed that improvements in swing-phase knee kinematics following treatment for stiff-knee gait were associated with postoperative decreases in knee extension moments during double support and increases in knee flexion velocity at toe-off. These data offer compelling evidence that stiff-knee gait results from problems that arise during late stance phase, in addition to possible abnormal muscle function during swing phase. The rectus femoris has the potential to contribute to excessive knee extension moments in double support, and thus the rectus femoris transfer may be an appropriate treatment for stance-phase contributions to stiff-knee gait. However, other factors may also contribute to excessive knee extension moments in double support, such as inadequate knee flexion moments generated by a weak gastrocnemius. Therefore, whether a rectus femoris transfer is necessary to improve stiff-knee gait in all cases is unclear. Future work should focus on identifying contributors to excessive knee extension moments in double support and developing treatment strategies that have the most potential to address the biomechanical causes of each individual's stiff-knee gait.

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Appendix A. Supplementary data

The online version of this article contains additional supplementary data. Please visit doi:10.1016/j.jbiomech.2005.01.015

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