Ankle Movements During Supine Kicking in Infants Born Preterm

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Background: Knowledge of musculoskeletal factors that influence supine kicking of infants born preterm has implications for early intervention. **Hypotheses:** Differences exist between infants born preterm and full-term in ankle kinematics during supine kicking, which are attributable to passive measures of the gastrocnemius/soleus (g/s) muscle tendon unit (MTU). **Subjects**: Twenty infants born full-term and 22 born preterm were measured at term, 6 weeks, and 12 weeks of age. **Outcome Measures:** Ankle kinematics during supine kicking and g/s MTU length. **Results:** Infants born preterm demonstrated less dorsiflexion, more plantar flexion, and more total ankle range during supine kicking. Gestational age explained 69% to 85% of the variability in MTU length from term to 12 weeks of age. MTU lengths explained 0% to 42% of the variance in ankle kinematics. **Conclusions:** Passive measures of the g/s MTU may inform clinicians about ankle kinematics in newborns to 12-week infants during supine kicking. **(Pediatr Phys Ther 2016;28:294–302)** *Key words: humans, infants, kinematics, motor control, motor development, preterm infants, systems theory*

INTRODUCTION

Infants born preterm at low risk have an increased risk of delay in motor development.[1-4] Dynamic systems theorists[5,6] state that movement emerges from the dynamic interaction of physiological and psychological subsystems in the context of environmental affordances. Research on motor development of infants born preterm has focused on disturbances in the neuromuscular subsystem, with the musculoskeletal subsystem receiving less attention in the literature. Understanding how and when subsystems drive variations in spontaneous movements in infants born preterm has important implications for physical therapy examination, evaluation, and prognosis.

0898-5669/110/283-0294
Pediatric Physical Therapy

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Grant Support: *Edward J. Leahy Center, University of Scranton, Scranton, Pennsylvania.*

The authors declare no conflicts of interest.

DOI: 10.1097/PEP.0000000000000252

Previous investigations of infants born preterm suggest that spontaneous supine kicking differs between infants born preterm with and without identified neurological disturbances and infants born full-term.[7-10] A fairly consistent difference observed in infants born preterm without identified neurological disturbances compared with infants born full-term is decreased overall lower extremity flexion during supine kicking.[7,11] Therefore, the amount of joint movement in infants born preterm may be less attributable to the neurological subsystem, with the musculoskeletal subsystem a promising contributor to altered active joint motion.

Muscle tendon unit (MTU) length has potential to modify wherein the range a muscle exerts force. Infants born preterm do not experience the last few weeks of fetal development characterized by prolonged flexion positioning, which potentially affects MTU length. Infants born preterm without identified neurological disturbances compared with infants born full-term have a shorter gastrocnemius/soleus (g/s) MTU and longer resting length over the first 12 weeks of adjusted age.[12,13] However, we do not currently understand how or if g/s MTU length influences active ankle movement.

MTU length may constrain active motion during supine kicking in infants born preterm. A decrease in peak dorsiflexion between infants born preterm and full-term during supine kicking[11] and an increase in the frequency of toe-strike versus foot-flat contact in new walkers[14] suggests infants born preterm without identified neurological disturbances have more plantar flexion joint motion. Heriza[11] suggested that viscoelastic muscle properties affect joint range in preterm infants, whereas Cioni et al[14] theorized that a predominance of plantar flexion during toe touch is related to active movement into lower extremity extension earlier in development. Correlation of active ankle motion and g/s MTU length during supine kicking in infants born preterm without identified neurological disturbances may reveal a relationship between the g/s MTU length and active ankle motion, provide insight into the influence of this subsystem, and focus research on intervention strategies influencing active muscle use, such as environmental modifications, which maximize dorsiflexion and limit plantar flexion.

The purpose of this longitudinal study was to examine the influence of the g/s MTU on ankle movements during supine kicking between infants born preterm without identified neurological disturbances and infants born full-term at term, 6 weeks, and 12 weeks of age. We hypothesized that (1) kicking duration and spatiotemporal organization of maximum ankle motions will be similar between infants born preterm and infants born full-term at all 3 ages; (2) infants born preterm will demonstrate decreased active maximum dorsiflexion (MDF) and increased maximum plantar flexion (MPF) during supine kicking at all 3 ages, and (3) passive measures of the g/s MTU length will explain a significant amount of variability of maximum active ankle movement in both groups of infants.

METHODS

The University of Scranton Institutional Review Board, Scranton-Temple Residency Program Institutional Review Board, Drexel University Institutional Review Board, and Community Medical Center's Executive Board approved this project before recruitment. All parents signed a consent form before participation.

Subjects

Before recruitment, power statistics for a power of 0.80 were calculated using effect sizes for MDF from Heriza[11] (calculated effect size [d] = 2.0, with 95% confidence interval [CI], 1.0-3.0). On the basis of these power analyses, each group required 20 subjects. Infants were recruited from 3 hospitals.

One hundred and twenty families with infants born full-term were asked to participate. Twenty-one families with 21 infants born full-term agreed to participate. One family declined participation before data collection. The other 20 infants participated in all 3 measurement sessions.

Neonatologists from 2 of the hospitals identified 33 families of infants born preterm who met the following inclusion criteria: (1) classified as low risk for developmental problems, (2) spent less than 72 hours on a ventilator, (3) had no evidence of neurological complications at discharge, and (4) had a benign medical course during their neonatal intensive care unit stay. Of these 33 families, 16 families and 22 infants participated in all 3 measurement sessions.

A total of 42 infants participated in the study: 20 in the full-term group born between 38 and 41 weeks of gestation and 22 in the preterm group born between 26 and 36 weeks of gestation. All infants had a normal term examination and no neurological, orthopedic, or genetic abnormalities. Table 1 contains group characteristics.

Instrumentation

Gastrocsoleus/soleus MTU length was measured using a 4-inch diameter goniometer with line designations for each degree. Positive angles were used to describe dorsiflexion measurement, and negative angles were used to describe plantar flexion with 0° representing a 90° relationship between the fifth metatarsal and the lower leg.

A Coda MPX 30 Motion Analysis System (Charnwood Dynamics, Rothley, Leicestershire, UK) was used to gather 3-dimensional data during supine kicking. A sensor unit, housing 3 masked linear arrays, was placed 8 ft and parallel to the infant and recorded 10 seconds of data at 200 Hz.

To determine kicking motion, 5 markers were placed on the (1) greater trochanter of the femur; (2) lateral knee joint; (3) lateral malleolus; (4) lateral heel at base of the fifth metatarsal; and (5) lateral side of the fifth metatarsal head. Marker placement reliability was assessed by repeated placement of markers on a 13-inch jointed doll with repeated kick simulation. The intraclass correlation coefficient (ICC) (3,1) value for 18 repeated joint end ranges was 0.99 (95% CI, 0.99-1.00). The ankle was modeled using the lateral knee joint and lateral malleolus markers to represent the leg segment and the lateral heel marker and fifth metatarsal head markers to represent the foot segment. The point of rotation for the ankle angle was the intersection of leg and foot segments. The knee was modeled using the femur, lateral knee joint, and lateral malleolus markers. The point of rotation for the knee was the lateral knee joint marker.

Subjects were placed on a custom-built table with a 26-by-36-inch tabletop raised 36 inches from the floor. The tabletop was covered with 1/16th inch thick, dense foam with a washable neoprene cover to ensure the infant was comfortable while not allowing the infant to gain trunk stability by sinking into the foam. A wooden bar was suspended over the length of the table. Both toys and an 8-marker box hung from this bar. The toys were directly above the infant's face so they could be seen, but too far away to be kicked and did not move in response to the subjects' movements.

TABLE 1
Group Characteristics for Infants Born Full-Term and Preterm

Characteristics	Full-Term Group (n = 20)	Preterm Group (n = 22)
Gestational age		
Range	38 wks, 2d to 41 wks, 0 d	26 wks, 3d to 34 wks, 5 d
Mean (SD)	39 wks, 2 d (6.4 d)	32 wks, 3 d (1 wks, 5.4 d)
Birth weight[a]		
Range	2750-4720 g	794-2604 g
Mean (SD)	3342 g (456 g)	1854 g (463 g)
Sex, n (%)		
Female	9 (45)	8 (36.4)
Male	11 (55)	14 (63.6)
Delivery method, n (%)		
Normal vaginal	15 (75)	8 (36.4)
Cesarian	5 (25)	14 (63.6)
Pregnancy type (%)[b]		
Singleton	20 (100)	13 (59)
Twin	0 (0)	8 (36.4)
Triplets	0 (0)	3 (13.6)

[a]Statistically significant differences in birth weight were found between infants born preterm and infants born full-term ($t_{(40)} = 10.9$, $P < .001$).
[b]No statistical differences were detected in maximal dorsiflexion or maximal plantar flexion between multiple (n = 11) and singleton (n = 13) pregnancies.

Procedures

Data collection occurred in the Movement Laboratory at the University of Scranton. Each infant's data collection session occurred within 7 days of birth, 6 weeks of age (±7 days), and 12 weeks of age (±7 days). Adjusted age was used for infants born preterm.

To encourage relaxation of the muscle, the g/s MTU length was collected on the right ankle while the infant was in behavioral state 1 (deep sleep), state 2 (light sleep), or state 4 (quiet, alert). After 3 repetitions of slow passive movement into end dorsiflexion to reduce creep, researchers measured the ankle angle with the slack removed from the relaxed MTU (A_0), and full stretch of the MTU (A_{Max}) (Figure 1). The A_0 was determined by palpating the initial point of maximum tautness in the Achilles tendon as the ankle was moved from plantar flexion to dorsiflexion and A_{Max} was the maximum length of the MTU. Both measures were obtained with the knee in full extension. Each measurement was taken twice with a third measure taken if the first 2 measures differed by more than 4°. A third measure was obtained on 15% of the measures for both examiners. Examiners were blinded to each other's results. Reliability between 2 examiners on 100 measurements of A_0 and 99 measurements of A_{Max} using ICC (2,1) was 0.99 (95% CI, 0.98-0.99) for A_0 and 0.95 (95% CI, 0.93-0.97) for A_{Max}. Additional details of MTU measurements and reliability for these infants[13] and other subjects[12,15] are described elsewhere.

Each infant was placed on the measurement table and all clothing was removed from the infant's right lower extremity. All other clothing was adjusted to allow free kicking. Five markers were attached to the infant's right lower extremity using hypoallergenic, double-sided tape. Half-inch neoprene straps were used to maintain the marker positions and keep the marker lead wires from tangling. Once the markers were placed, one researcher interacted with the infants to encouraged kicking. Ten-second trials were repeated until the researchers had at least 3 trials with kicks in each trial.

Kicking data were collected when the infants were in state 3 (drowsy), 4 (quiet, alert), or 5 (active, awake).[16,17] If the infant moved into state 1 (deep sleep), 2 (light sleep), or 6 (crying), data collection was stopped and attempts were made to assist the infant to move into state 3, 4, or 5.

Data Reduction

Using the Coda's connected marker model, the distance between the heel and femur marker was graphed in the horizontal direction and used to visually detect supine kicks. Ankle and knee joint angles were graphed and viewed simultaneously in each 10-second trial. Interrater reliability on 25% of the sample for 2 scorers was ICC (2,1) = 0.99 (95% CI, 0.99-1.00) for identifying kicks and all other data.

A kick was defined as a movement with both lower extremity flexion and extension.[18] Two kicking phases were identified. Five frames of continuous horizontal motion of the heel marker toward the femoral marker initiated each flexion phase, with 5 frames of continuous horizontal motion of the heel marker away from the femoral marker initiated the extension phase. Each kicking phase ended with 5 frames of continuous horizontal reversal of the movement or 5 frames of no movement.[18] Kicks were eliminated if (1) a marker was out of view for more than 5 frames, (2) the heel of the kicking leg was placed on the table, or (3) the knee joint range did not change during the kick (remained extended or flexed).

Outcome Measures

Ankle Kinematics. MPF and MDF were considered to be the limits of observed ankle movement. For each infant at each measurement session, 2 kicks were identified, 1 each for MDF and MPF. The goal was to compare the limits of active ankle movement into dorsiflexion and plantar

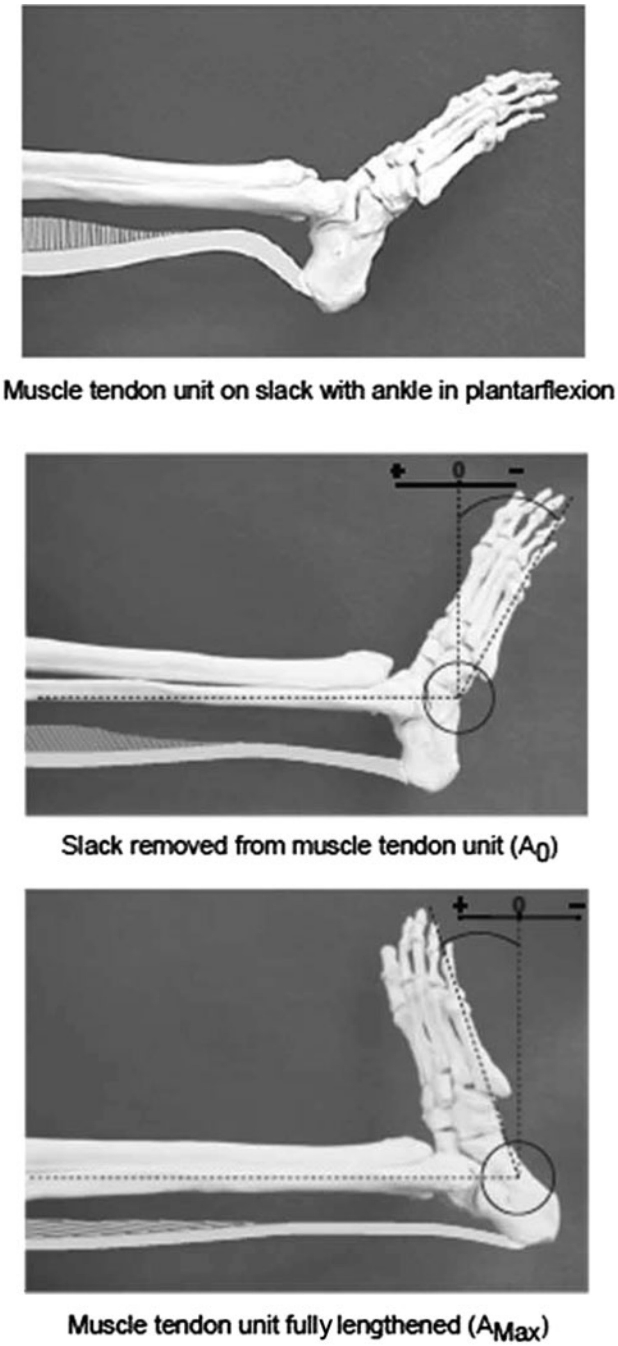


Fig. 1. Model representing the gastrocsoleus muscle-tendon unit on slack (top), A_0 slack removed (middle), and A_{Max} fully lengthened (bottom). Goniometric measurement occurs with goniometer arms aligned with long axis of the fibula and long axis of the fifth metatarsal. The origin is a 90° angle between the goniometer arms.

flexion and not the average maximum movement of many kicks into dorsiflexion or plantar flexion; therefore, we identified the largest observed ankle movement into dorsiflexion (MDF) and plantar flexion (MPF) for correlation with maximum passive g/s MTU length. The absolute difference between the MDF and MPF was calculated as the total ankle range (TAR). Because the g/s MTU crosses the knee and ankle, knee flexion angles at MPF and MDF were recorded.

Kicking Characteristics. For kicks with the identified MDF and MPF, the phase (extension or flexion) and the calculated duration (stop time minus start time) were recorded. After normalization of each kick to assume 0% to 50% extension motion and 51% to 100% flexion motion, the points in the kick where MDF and MPF occurred were also recorded. All comparisons of kicking duration met assumptions of normality and homogeneity, except homogeneity in newborn plantar flexion duration. With observations of less than 10 in some group comparisons, nonparametric analyses were used. Mann-Whitney *U* tests demonstrated no statistical difference in kicking duration of flexion and extension phases containing MDF; therefore, kicking durations for MDF and MPF were compared between groups and over age without controlling for the phase containing MDF or MPF.

Gastrocsoleus/soleus MTU Length. Measures of A_0 and A_{Max} taken in each infant at each age were averaged. Using the averaged A_0 and A_{Max} measurements, the absolute difference between these measurements was used to calculate A_0 to A_{Max}.

Data Analysis

Differences in Kicking Characteristics. Before all statistical analyses, data were examined for normality and homogeneity. To compare kicks in which MDF and MPF were observed, 3 kicking characteristics were examined: (1) kicking phase, either flexion or extension, where MDF or MPF occurred, (2) duration of the kick containing MDF or MPF, and (3) normalized point within the kicking pattern where MDF and MPF occurred. These kicking characteristics were examined using chi-square analyses and 2-way, mixed-model analysis of variances (ANOVAs).

Differences in Active Ankle Kinematics. Two-way, mixed-model ANOVAs (2 groups × 3 ages) with Bonferroni post-hoc analysis were used to examine differences in groups, over ages, and group × age interactions in MDF, MPF, TAR, and knee flexion at both MDF and MPF.

Determinants of Active Ankle Kinematics. Regression analyses were used to examine the variance in maximum ankle kinematics explained by passive muscle-tendon unit length measures (A_0 and A_{Max}) and knee position at MDF and MPF.

RESULTS

Differences in Kicking Characteristics

Kicking Phase, Flexion or Extension, Where MDF or MPF Occurred. The kicking phase containing MDF and MPF for both groups over age is listed in Table 2. When examining the percentage of infants in each group who demonstrated MDF and MPF in the flexion phase and the extension phase, no significant group differences were found between the full-term and preterm groups in the percentage of MDF occurring in either the flexion or extension phase, with no significant results for the percentage of MPF occurring in either the flexion or extension phase.

Because there were no group differences, group data were combined to more specifically examine the effect of age. Frequency counts over term, 6 weeks, and 12 weeks of age were examined for both MDF and MPF, with no differences in which phase of kicking, flexion, or extension, found for MDF or MPF.

Duration of the Kick Containing MDF or MPF (Figure 2). No significant group effects or interactions were detected in the duration of the kicking phase for MDF or MPF.

Normalized Point in Kick Where MDF and MPF Occurred (Figure 3). No significant results were observed for group, age, or interaction for the point where MDF occurred in the kick. No significant results were found for group or interaction for the point where MPF occurred. A significant effect for the point in the kick where MPF occurred was detected over age ($F_{(2,80)} = 3.44$, $P = .04$). Post-hoc analysis indicated that MPF occurred early in the flexion phase (mean = 52.5%) at term age and late in the extension phase (mean = 42.5%) at 12 weeks of age.

Differences in Maximum Ankle Kinematics

Significant main effects for group differences were found in MDF ($F_{(1,40)} = 15.98$, $P < .001$), MPF ($F_{(1,40)} = 28.50$, $P < .001$), and TAR ($F_{(1,40)} = 4.45$, $P = .04$). The preterm group demonstrated less ankle dorsiflexion (mean MDF = 25.3° preterm group vs 34.8° full-term group), more plantar flexion (mean MPF = 52.5° preterm vs 36.2° full-term), and larger TAR values (mean TAR = 77.8° preterm vs 72.1° full-term). MDF was not significantly different over age. There were significant differences by age in MPF ($F_{(2,80)} = 5.63$, $P = .005$) and TAR ($F_{(2,80)} = 4.39$, $P = .016$). MPF differed between term (mean = −38.9) and 6 weeks of age (mean = −47.1, $P = .015$) and between term and 12 weeks of age (mean = −47.2, $P = .015$). TAR differed between term (mean = 69.6) and 12 weeks of age (mean = 77.8, $P = .05$). The difference between term and 6 weeks of age (mean = 77.5) on TAR was not significant. There were no significant interactions for MDF, MPF, or TAR. There were no significant differences for the

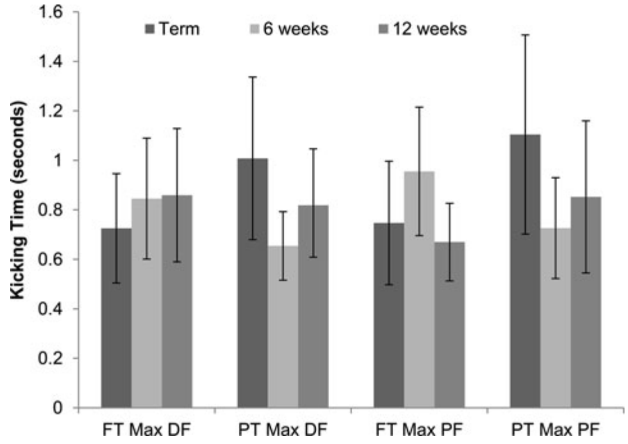


Fig. 2. Mean of total kicking time (seconds) and 95% confidence intervals for kicks demonstrating maximum plantar flexion (MPF) and maximum dorsiflexion (MDF) in infants born full-term (FT) and preterm (PT). No significant main effects or interactions were found for the duration of MDF or MPF.

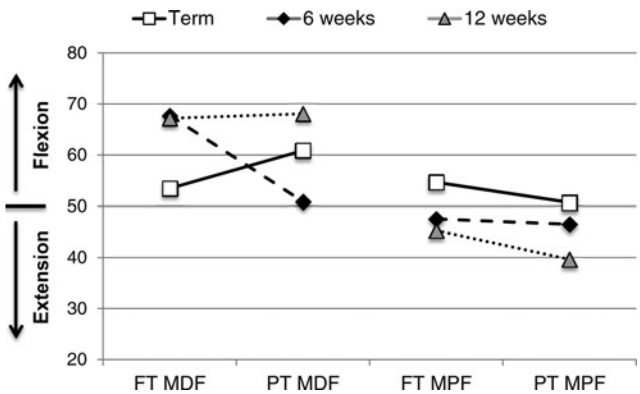


Fig. 3. The normalized range where maximum plantar flexion (MPF) and maximum dorsiflexion (MDF) occurred in the full-term (FT) and preterm (PT) infants at term age, 6 weeks of age, and 12 weeks of age. Extension phase of the kick is normalized for 0% to 50% of the kick, and the flexion phase is normalized for 51% to 100% of the kick. A significant difference over age was determined for where in the range MPF was observed with MPF occurring early in the flexion phase at term age and late in the extension phase at 12 weeks of age. No other significant comparisons were detected.

TABLE 2

Phase of Kicking of Maximal Dorsiflexion and Maximal Plantar Flexion[a]

	Full-Term Group (n = 20)		Preterm Group (n = 22)	
Kicking Phase Age	Extension n (%)	Flexion n (%)	Extension n (%)	Flexion n (%)
MDF				
Term	10 (50)	10 (50)	9 (41)	13 (59)
6 wks	6 (30)	14 (70)	10 (45)	12 (55)
12 wks	4 (20)	16 (80)	6 (27)	16 (73)
MPF				
Term	10 (50)	10 (50)	10 (45)	12 (55)
6 wks	11 (55)	9 (45)	12 (55)	10 (45)
12 wks	14 (70)	6 (30)	16 (73)	6 (27)

Abbreviations: MDF, maximal dorsiflexion; MPF, maximal plantar flexion.
[a]No significant differences were detected between groups or across ages.

main effect of group, the main effect of age, or the interaction group × age in knee flexion angles at MDF or MPF. Means, standard deviations for groups and age on MDF, MPF, TAR, and knee range for MDF and MPF are listed in Figure 4.

Relationship Between Ankle Motion and Muscle-Tendon Unit Length

A preliminary examination of correlations between the planned predictor variables, g/s MTU length measures, knee range at MDF and MPF, and gestational age at birth, revealed significant correlations between gestational age and A_0 ($r = 0.83$-0.92, $P < .001$) with smaller, but significant correlations between gestational age at birth and A_{Max} and gestational age at birth and A_0 to A_{Max} ($r = 0.30$-0.63, $P = .03$ to $<.001$) (Table 3).

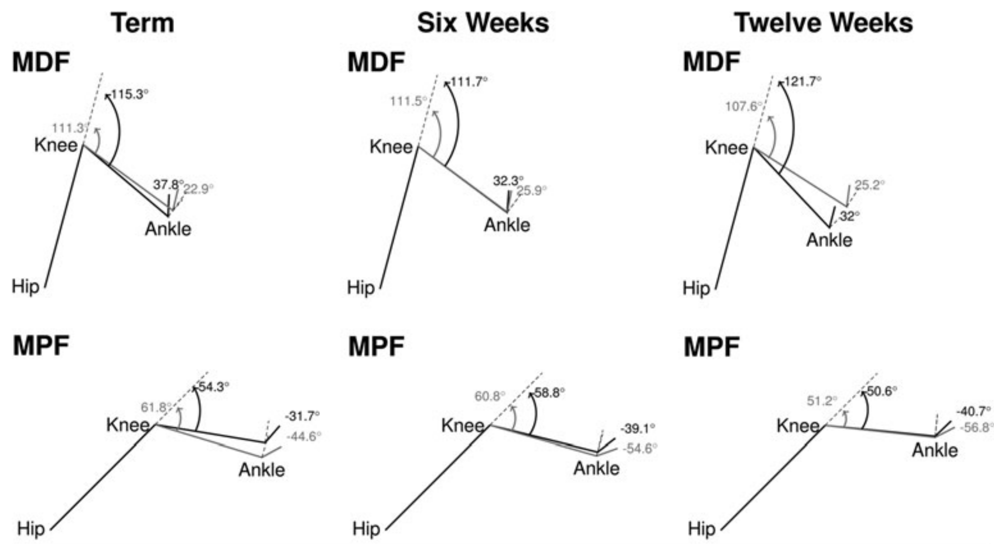
High correlations between gestational age and passive muscle unit length suggest a strong relationship between these predictors and a potential issue with multicollinearity. This multicollinearity was also suggested with stepwise regression analyses. When using both gestational age and g/s MTU length to predict maximum ankle kinematics, entering either predictor first resulted in a significant regression equation, but eliminated a significant contribution of the other predictor. This result supports the hypothesis that as gestational age progresses, g/s MTU length and potentially multiple other subsystems may be altered, which in turn modify maximum ankle kinematics. We suggest that additional weeks in utero, or an increase in gestational age, have the potential to directly affect g/s MTU length through prolonged positioning. The g/s MTU,

TABLE 3

Correlations, Coefficients of Determination, and Significance Between Gestational Age at Birth and Measures of Muscle-Tendon Unit Length at Term, 6 Weeks, and 12 Weeks of Age

Term (n = 42)	6 wks (n = 42)	12 wks (n = 42)
GA and A_0		
$r = 0.83$	$r = 0.85$	$r = 0.92$
$R^2 = 0.69$	$R^2 = 0.72$	$R^2 = 0.85$
$P < .001$	$P < .001$	$P < .001$
GA and A_{Max}		
$r = 0.63$	$r = 0.50$	$r = 0.50$
$R^2 = 0.40$	$R^2 = 0.25$	$R^2 = 0.25$
$P < .001$	$P < .001$	$P < .001$
GA and A_0 to A_{Max}		
$r = 0.30$	$r = 0.53$	$r = 0.57$
$R^2 = 0.09$	$R^2 = 0.28$	$R^2 = 0.32$
$P = .026$	$P < .001$	$P < .001$

Abbreviation: GA, gestational age.



	Term		6 weeks		12 weeks	
	Full term (n=20)	Preterm (n=22)	Full term (n=20)	Preterm (n=22)	Full term (n=20)	Preterm (n=22)
MDF, mean (sd)						
Ankle	37.8 (10.9)	22.8 (13.0)	32.3 (8.9)	25.9 (11.6)	32.0 (11.0)	25.2 (12.0)
Knee	115.3 (29.3)	111.3 (20.5)	111.7 (26.8)	111.5 (21.5)	121.7 (19.1)	107.6 (28.7)
MPF, mean (sd)						
Ankle	-31.7 (10.8)	-44.6 (15.7)	-39.1 (12.2)	-54.6 (10.1)	-40.7 (14.1)	-56.8 (15.2)
Knee	54.3 (31.4)	61.8 (27.7)	58.8 (25.9)	60.8 (26.8)	50.6 (13.6)	51.2 (32.0)
TAR						
Ankle	70.8 (3.5)	68.4 (3.5)	72.9 (2.4)	82.1 (2.4)	72.7 (3.3)	83.0 (3.8)

Fig. 4. Means and standard deviations for maximum plantar flexion (MPF), maximum dorsiflexion (MDF), and knee flexion at MDF and MPF for infants born full-term (signified by black) and infants born preterm (signified by gray). Significant differences detected for MDF, MPF, and total ankle range (TAR) between groups and over age for MPF (term <6 weeks and term <12 weeks) and TAR (term <12 weeks). Hip flexion angles were not documented so these were standardized at 75° for MDF and 45° for MPF and do not reflect actual values in our subjects.

which is designed to exert force at the ankle and knee, has the potential to directly affect MDF and MPF, whereas altered gestational age does not have the same potential to directly drive changes in maximum ankle kinematics at term, 6 weeks, or 12 weeks of age. For these reasons, gestational age was removed as a predictor for maximum ankle kinematics.

Measures of MTU length explained a significant amount of variability in MDF, MPF, and TAR at all ages except for MDF and TAR at 6 weeks. Knee range at MPF contributed to the prediction equations for TAR at term and knee range, combined with A_0 contributed to the equations for MPF and TAR at 12 weeks. At 6 weeks of age, none of the variables (A_0, A_{Max}, A_0 to A_{Max}, or knee range at MDF or MPF) predicted MDF or TAR. The highest explained variance was 42% (41% adjusted) in MDF at term age using A_0 and, using both A_0 and knee flexion at MPF, 34% (31% adjusted) of the variability in MPF at 12 weeks, and 33% (28% adjusted) of the variability in TAR at 12 weeks. Less variability in maximum ankle kinematics (12%-22%, 10%-20% adjusted) was explained in MDF at 12 weeks, MPF at term and 6 weeks, and TAR at term age using our predictors. Table 4 contains the results of the stepwise regression analysis.

DISCUSSION

Our results support our hypotheses that infants born preterm without identified neurological disturbances and infants born full-term demonstrate differences in supine kicking ankle kinematics between term and 12 weeks of age. Although similarities in kicking characteristics between infants born preterm and full-term were observed, our data support the hypothesis that the differences in maximum ankle kinematics are influenced by the length of the g/s MTU and knee position. These data suggest that the length of the MTU influenced motion observed at specific joints and consequently, ankle movement.

Differences in Kicking Characteristics

Our findings did not detect differences in the kinematics of some of the kicking characteristics including the timing of supine kicking movements between infants born preterm and full-term and over the first 12 weeks, with the exception of MPF timing within the kicking phases. Heriza[11] reported in infants born preterm at term age and infants born full-term that the ankle initiated both the flexion and extension phases of supine kicking. Although our data do not indicate which joint initiated each phase, the results suggest that the ankle is not initiating the motion because the ankle does not reach MPF until after the initiation of the flexion phase. Passive forces produced during the initial flexion movement of the lower extremity could also explain an increase in plantar flexion early in the flexion phase. After 12 additional weeks of experience, the infants could learn to accommodate for these passive forces.[19,20] With no differences detected between groups, our data are consistent with the hypothesis that shorter g/s MTU length detected in infants born preterm is not altering the some of the kicking characteristics we examined.

TABLE 4

Stepwise Regression Analysis Results Using A_0, A_{Max}, A_0 to A_{Max}, and Knee Range as Predictors of Maximal Dorsiflexion, Maximal Plantar Flexion, and Total Ankle Range

	Term (n = 42)	6 wks (n = 42)	12 wks (n = 42)
MDF			
Predictors	A_0	None	A_{Max}
ANOVA	$F = 29.4$, $P < .001$[a]		$F = 6.9$, $P = .01$[a]
Variance	$R = 0.65$, $R^2 = 0.42$, adjusted $R^2 = 0.41$		$R = 0.38$, $R^2 = 0.15$, adjusted $R^2 = 0.13$
Prediction equation	MDF = 43.6° + (A_0 × 1.2)[a]		MDF = −14.9° + (A_{Max} × 0.97)[a]
MPF			
Predictors	A_0	A_0	A_0, knee ROM at MPF
ANOVA	$F = 11.0$, $P = .002$[a]	$F = 8.6$, $P = .005$[a]	$F = 10.2$, $P < .001$[a]
Variance	$R = 0.47$, $R^2 = 0.22$, adjusted $R^2 = 0.20$	$R = 0.42$, $R^2 = 0.18$, adjusted $R^2 = 0.16$	$R = 0.59$, $R^2 = 0.34$, adjusted $R^2 = 0.31$
Prediction equation	MPF = −29.3° + (A_0 × 0.92)[a]	MPF = −39.6° + (A_0 × 0.85)[a]	MPF = −47.1° + (A_0 × 1.7) + (knee ROM × 0.26)[a]
TAR			
Predictors	Knee ROM at MPF	None	A_0, knee ROM at MPF
ANOVA	$F = 5.6$, $P = .02$[a]		$F = 6.3$, $P = .001$[a]
Variance	$R = 0.35$, $R^2 = 0.12$, adjusted $R^2 = 0.10$		$R = 0.58$, $R^2 = 0.33$, adjusted $R^2 = 0.28$
Prediction equation	TAR = 80.9° + (knee ROM × −0.18)[a]		TAR = −61.9.9° + (A_0 × −3.0) + (knee ROM × −0.20)[a]

Abbreviations: A_0, ankle angle with the slack removed from the relaxed muscle tendon unit; A_{Max}, ankle angle with full stretch of the muscle tendon unit; ANOVA, analysis of variance; MDF, maximal dorsiflexion; MPF, maximal plantar flexion; ROM, range of motion; TAR, total ankle range.
[a]Equation significant.

Differences in Maximum Ankle Kinematics and Knee Flexion

Maximal ankle movements in this preterm group support our hypothesis that shorter g/s MTU length measurements contribute to active ankle movements in more plantar-flexed ranges. No corresponding change was found in knee flexion range at the point of maximum ankle kinematics, suggesting that a different combination of active motion between the ankle and knee is used by the 2 groups of infants.

Increased plantar flexion during supine kicking in the preterm group may affect the ankle and knee movement patterns available to meet the demands of supported standing and walking. Whereas increased plantar flexion may not hinder supine kicking,[21] increased plantar flexion could affect the movement pattern used during foot contact in supported stepping.[22] If increased plantar flexion with no change in knee flexion, observed between term age and 12 weeks, continues until initiation of walking, this change could explain the increased frequency of toe touch observed by Cioni et al[14] in early walkers born preterm.

Relationship Between Ankle Kinematics and MTU Length

The strong linear relationship between gestational age and the resting length of the g/s muscle-tendon unit, at term age and continuing through 12 weeks of age (Table 3), is consistent with theories on gestation and changes in muscle tone,[23-27] which is assessed through examination of joint resistance to movement (passive tone) and righting reflexes (active tone).[25,26] Our data suggest that this change is not attributable only to muscle tone or maturation of the nervous system, but might partially be explained by MTU length. Previously, we demonstrated that the mean g/s MTU in infants born preterm was shorter than the mean g/s MTU in the full-term group[12,13] and may limit MDF and alter where around the joint the muscle can actively contract. Through positioning of the lower limb, uterine fetal position versus lying on a mattress, the MTU is shaped, which contributes to ankle kinematics.

Variability in the prediction equations over age may highlight changes in the contribution of the g/s to active ankle movements as the infants mature with 2 interesting trends observed in the equations (Table 4). First, although more variability in MDF is explained at term age than at 12 weeks of age, we see an opposite trend in the variability explained in MPF and TAR. This difference may be related to the fact that MTU measurements of ankle plantar flexion were used to predict maximal kinematics. Movement into MDF would result in stretching the g/s MTU. When examining the predictors for MDF, the resting length (A_0) plus 43.6° predicts MDF at term age, whereas the lengthened MTU (A_{Max}) minus 14.9° predicts MDF at 12 weeks. The switch in predictor variables may indicate a switch from MDF occurring in relation to sensation regarding slack removed from the system (A_0) at term age to cessation of dorsiflexion before maximal length (A_{Max}) of the muscle at 12 weeks. The influence of the g/s on MDF decreases from 42% at term age to 15% at 12 weeks, suggesting the g/s MTU has less effect on MDF at 12 weeks.

In contrast, during active plantar flexion, the muscle belly would be shortening and active. Overage, this increasing influence of A_0, suggests the g/s MTU length is contributing more to MPF at an age when these subjects produced larger MPF movements. During uterine confinement, movements into plantar flexion would be limited, with increased plantar flexion possible in the extrauterine environment. Increasing the influence of the g/s MTU length on MPF is consistent with Thelen and Cooke's[28] observations of less activity in g/s EMG during supported stepping at newborn age with increased activation in the g/s at 2 months of age. After 12 weeks of kicking rehearsal, contribution of both the g/s MTU length and knee range of motion to predict MPF could theoretically suggest many neurological or structural changes; however, it could also suggest the infant is integrating sensory input from the knee and ankle to produce MPF.

A second interesting trend, the decrease in predictors explaining MDF and TAR at 6 weeks, may indicate increased influence of another subsystem or muscle on active ankle movement. After birth, the infant adapts to a variety of changes including altered sensory input and novel movement into extended positions in a gravity-enhanced environment. During the 6-week measurement, the inability to predict MDF and TAR with g/s MTU length suggests another subsystem, or potentially dorsiflexor muscles are driving MDF. The variability in predictor equations over age may be a reflection of adjusting subsystem influence on ankle movement and evidence of motor learning.

Implications for Practice and Research

Our findings support the assumption that the musculoskeletal subsystem contributes to early coordination during supine kicking between infants born preterm without identified neurological disturbances and infants born full-term at term, 6 weeks, and 12 weeks. Differences in the g/s MTU length may be attributed to uterine positioning during the end of gestation and in turn, may affect active ankle motion and the relationship between the ankle and knee during supine kicking. We recommend that therapists examine ankle MTU length using a goniometer to evaluate how passive length affects active ankle movement during supine kicking. For infants who demonstrate ankle movements in plantar-flexed positions during supine kicking, recommendations for monitoring and intervention include positioning and rehearsal of tasks, which facilitate increased dorsiflexion, isolated joint movements,[29,30] and movement of the lower limb against gravity.[29] Active rehearsal of specific tasks for infants post/preterm without identified neurological disturbances, which stimulate the g/s to contract in positions of dorsiflexion combined with functional joint patterns used during gait, may be useful in supporting the development of upright mobility.

Further research is recommended to characterize changes in the g/s MTU length in infants born preterm during the first 18 months. If infants born preterm without identified neurological disturbances continue to demonstrate shortening in MTU length, additional research is recommended to determine the relationship between MTU length and active ankle motion in early walking.

ACKNOWLEDGMENTS

The authors thank Mr Rob Octavio for his assistance with Figure 1, Dr Richard C. Beuttler for his assistance with Figure 4, and Dr James Roberge for his advice on statistical methods used in this article. We would thank the families and infants who dedicated precious time to participate in this study and made this work possible.

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