2016-10

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Original Publication Citation

Ridge, S, Henley, J, Manal, K, Miller, F & Richards, J. (2016) Biomechanical analysis of gait termination in 11-17 year old youth at preferred and fast walking speed. Human Movement Science, 49, 178-185.

BYU ScholarsArchive Citation

Ridge, Sarah T.; Henley, John; Manal, Kurt; Miller, Freeman; and Richards, James G., "Biomechanical analysis of gait termination in 11–17 year old youth at preferred and fast walking speeds" (2016). *Faculty Publications*. 2013.
https://scholarsarchive.byu.edu/facpub/2013

Biomechanical analysis of gait termination in 11–17 year old youth at preferred and fast walking speeds

Sarah Trager Ridge, John Henley, Kurt Manal, Freeman Miller, James G. Richards

Abstract

In populations where walking and/or stopping can be difficult, such as in children with cerebral palsy, the ability to quickly stop walking may be beyond the child's capabilities. Gait termination may be improved with physical therapy. However, without a greater understanding of the mechanical requirements of this skill, treatment planning is difficult. The purpose of this study was to understand how healthy children successfully terminate gait in one step when walking quickly, which can be challenging even for healthy children. Lower extremity kinematic and kinetic data were collected from 15 youth as they performed walking, planned, and unplanned stopping tasks. Each stopping task was performed as the subject walked at his/her preferred speed and a fast speed. The most significant changes in mechanics between speed conditions (preferred and fast) of the same stopping task were greater knee flexion angles (unplanned: +16.49 ± 0.54°, $p = 0.00$; planned: +15.75 ± 1.1°, $p = 0.00$) and knee extension moments (unplanned: +0.67 ± 0.02 N/kgm, $p = 0.00$; planned: +0.57 ± 0.23 N/kgm, $p = 0.00$) at faster speeds. The extra range of motion in the joints and extra muscle strength required to maintain the stopping position suggests that stretching and strengthening the muscles surrounding the joints of the lower extremity, particularly the knee, may be a useful intervention.

Keywords

Gait termination, Gait, Healthy children

1. Introduction

Gait termination can be a challenge for certain populations, particularly while walking at greater than preferred speeds (Meier, Desrosiers, Bourassa, & Blaszczyk, 2001). The inability to terminate gait quickly can increase the risk of falling or lead to an accident, such as a collision with another person or object. It has been suggested that individuals who have difficulty with this task may be able to improve their ability to stop walking quickly and safely (Serrao et al., 2013). In order to improve gait termination ability in people with physical and/or neurological challenges, the kinematics and kinetics of gait termination in healthy subjects should be understood.

Much of the previous research in this area has focused on ground reaction forces during stopping tasks, while very little has focused on the lower extremity joint mechanics necessary to perform this function (Bishop, Brunt, & Marjama-Lyons, 2006; Bishop, Brunt, Pathare, & Patel, 2002; Hreljac, 1995; Tirosh & Sparrow, 2005; Vrieling et al., 2008; Wikstrom, Bishop, Inamdar, & Hass, 2010; Wikstrom & Hass, 2012). Studies have shown that as walking velocity increases, so do ground reaction forces during gait termination and the number of steps that are required to stop (Jaeger & Vanitchatchavan, 1992; Serrao et al., 2013; Sparrow & Tirosh, 2005; Tirosh & Sparrow, 2004; Tirosh et al., 2005) Similar responses, such as increased number of steps to stop, are found in a pathological population during preferred speed walking and stopping, when compared to healthy subjects (Serrao et al., 2013; Vrieling et al., 2008).

Previous research has shown that braking forces applied to the lead leg were significantly higher as walking speed increased (from preferred speed to 125% and 150% of preferred speed) (Bishop et al., 2002). No between-speed differences existed for peak braking ground reaction force applied to the trailing leg, indicating that subjects rely more on the lead limb to stop than the trailing leg. The importance of the lead limb during the stopping tasks is also indicated in another study that showed that healthy adults (ages 34–70) exhibited well-defined patterns of hip and knee flexion and extension during unplanned gait termination (Serrao et al., 2013). In comparison, subjects with cerebellar ataxia had significantly different peak hip and knee flexion and extension angles in the lead limb compared to age-matched controls. Based on the patients' difficulty with stopping in one step, the researchers concluded that rehabilitation or treatment to assist these patients in learning an effective method of gait termination may be warranted.

The goal of this study was to gain a greater understanding of certain mechanical characteristics exhibited by healthy youth during planned and unplanned stopping tasks, particularly at a faster walking speed as this provides a challenge to healthy subjects. Documenting the response of this population to a challenging stopping task may provide information that will be helpful in planning therapeutic interventions for individuals (e.g. those with cerebral palsy or cerebellar ataxia) who have difficulty terminating gait, even at preferred walking speeds. It was hypothesized that the magnitude of peak knee and hip flexion angles, peak ankle plantarflexion moment, and peak knee and hip extension moments would be greater during the same gait termination task (planned or unplanned) after fast walking than after preferred speed walking. We also hypothesized that these variables would be greater during unplanned stopped than during planning stopping, regardless of speed.

2. Methods

2.1. Participants

Fourteen healthy, typically developing youth between the ages of 11–17 years old (mean = 14.4 ± 2.1 years; height = 154.4 ± 15.7 cm, mass = 57.7 ± 17.7 kg) participated in this study. The study was approved by the local research ethics committee and informed consent and assent were obtained from all participants.

2.2. Experimental protocol

At the beginning of the data collection, descriptive measurements including height, weight, foot length, and arm dominance were recorded for each subject. Reflective markers were applied to anatomical landmarks including the sacrum and bilaterally on the dorsum of the bare foot, heel, lateral malleolus, distal tibia, lateral femoral epicondyle, distal thigh, anterior and posterior superior iliac spines acromion process, upper arm, olecranon process, forearm, and the distal radial-ulnar joint to create 12 segments. The motion analysis portion of the data collection included a 1-s static trial, followed by an average of 35 walking and stopping trials. Motion data was collected using 10 Eagle Digital Motion Analysis Cameras (Motion Analysis, Santa Rosa, CA, USA) at a sampling rate of 60 Hz. Force plate data was collected at a rate of 960 Hz from 4 AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) located at least 4 m from the start of the walkway.

The first 3–5 walking trials were used to establish the subject’s preferred walking speed along the 8 m walkway. Custom LabView software was used to calculate walking velocity by streaming marker data from the Motion Analysis system in real-time. The subject’s preferred speed was calculated by averaging the walking velocities from three trials. A target speed for the 150% preferred speed trials was then calculated. This target speed was chosen to provide a sufficient increase from preferred speed, but remain lower than the typical walk-to-run preferred transition speed of approximately 2.0 m/s (Hreljac, 1995).

Subjects completed four sets of stopping trials in the following order: (1) unplanned stop at preferred speed (unplanned-preferred), (2) planned stop at preferred speed (planned-preferred), (3) unplanned stop at fast speed (unplanned-fast), and (4) planned stop at fast speed (planned-fast). This order was selected to minimize the total number of trials performed by each subject. It was easier for subjects to match their speeds to previous trials than alternate between preferred and fast speeds. In addition, we anticipated that subjects would need a greater number of fast trials to complete 3 successful trials, so we did those last in order to ensure that more successful trials (preferred speed) could be collected within the pre-defined limit of 50 trials.

During the unplanned stopping trials, subjects monitored their walking velocity by watching 2 sliders projected onto a screen at the end of the walkway – one slider represented their current position in the room, while the other represented the position they should be at based on their target speed (the previously measured preferred speed or 150% preferred speed) (Ridge & Richards, 2011). At a random heel strike on their dominant leg (same side as the self-reported dominant arm), a stop sign appeared on the screen, giving them the cue to stop as quickly as possible (Ridge, Henley, Manal, Miller, & Richards, 2013). During unplanned stopping trials, subjects were told to “freeze” as quickly as they could after they saw the signal to stop and to remain in that position until the investigator told them to move again. This resulted in the subject seeing the signal (just after dominant leg heel strike), then stopping with the non-dominant leg in front (Fig. 1). The signal to resume movement was given after subjects maintained their stopped position (lead limb on a force plate, trailing limb behind) for approximately 2 s. During planned stopping trials, subjects were instructed to walk at the preferred or fast speed until they reached a specific force plate, at which point they would bring their feet together and freeze (Fig. 1). Their instructions included a reminder to maintain their walking speed until they reached the designated force plate.

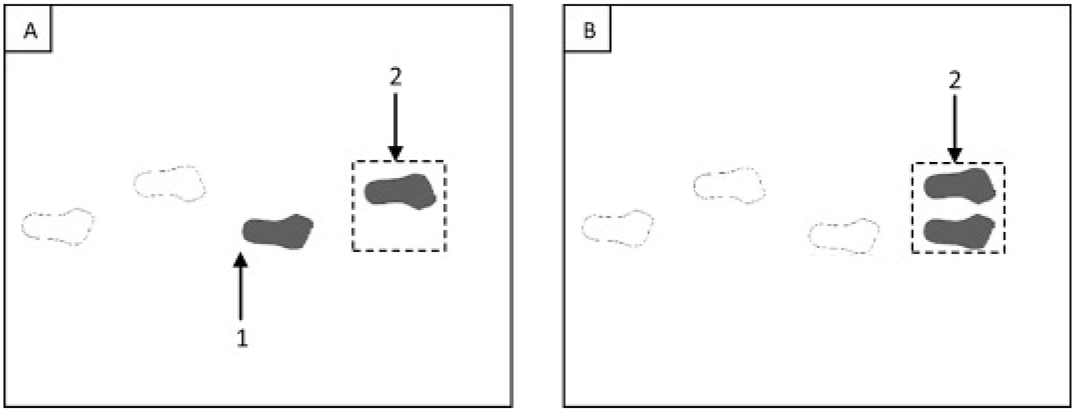

Fig. 1. Overhead view of data collection volume as a right arm dominant subject completed stopping trials – (A) Unplanned stop, (B) Planned stop. The dark gray footsteps represent a subject's feet in the stopped position. The dashed square in the volume represents the force plate. During unplanned stopping, the stop signal was given at penultimate foot contact (1). All data that was analyzed statistically was taken from the lead limb during terminal stance (2).

Data were collected from the time subjects entered the volume until at least 2 s after they stopped. If subjects were unable to complete all of the trials (including walking, unplanned-preferred, planned-preferred, unplanned-fast, and planned-fast) within 50 trials, the data collection session was ended.

2.3. Data analysis

Marker positions were tracked and filtered with a 6 Hz Butterworth filter in Motion Analysis Cortex software. Three-dimensional lower body joint angles and internal joint moments were calculated in Visual 3d (C-Motion, Inc., Germantown, MD, USA). Moments were normalized to the subject's height * body mass.

Step length was calculated as the distance between subsequent heel strikes during walking steps taken prior to the terminal step. Stop step length was the distance between the last walking step heel strike and the terminal foot contact. Approach velocity was calculated for each trial by calculating the average forward velocity during the 0.5 s prior to the penultimate foot contact (Fig. 1). Due to the variability of subjects' heights, approach velocity and step lengths are normalized by the Froude number and leg length, respectively (Hof, 1996). For the purposes of this study, subjects were considered stopped when the forward velocity of the subject's center of mass (COM) dropped below 5% of his/her preferred forward velocity. For unplanned stopping trials, time to stop was the difference between when the stop signal was given (penultimate foot contact) and when the COM stop was achieved.

Peak hip and knee flexion angles were analyzed for the lead limb during the terminal stance phase. This stance phase was defined as the period between foot contact of the stop step (terminal foot contact) and termination of the forward motion of the COM. Peak plantarflexion moments, peak knee extension moments, and peak hip extension moments were analyzed for all trials in which the stop step occurred within one step of the appearance of the stop signal and the lead foot was on a force plate. All peaks were picked from two or three trials of each stopping task, then averaged prior to use in statistical analysis. Timing of peaks was calculated as a percentage of the "stop stance" phase (terminal foot contact to COM stop – positions 2 and 4 on Fig. 1). All kinematic and kinetic variables were also calculated as described during the stance phase of preferred speed walking.

The independent variables were speed (condition) and planned or unplanned (task). The dependent variables were the magnitude and timing of the peak hip and knee flexion angles, peak ankle plantarflexion moment, and peak hip and knee extension moments during terminal stance. Repeated measures ANOVAs were used to evaluate the effects of the condition and task on the dependent variables (alpha = 0.01). When statistical differences were found, a Tukey's post hoc test was run to determine where the differences occurred. Statistical analyses were performed using the Statistica statistical analysis package by StatSoft (Tulsa, OK, USA). Statistical analyses related to the walking data were reported in a previous paper (Ridge et al., 2013).

3. Results

Subjects needed an average of 35.3 ± 6.1 trials to perform 3 trials of each condition. However, some subjects' data were excluded from analysis for certain conditions, based on difficulties during data collection. One subject did not achieve a fast walking speed (150 ± 10% of her preferred speed) during unplanned-fast and planned-fast trials. Four additional subjects' data were excluded from kinetic analysis of the unplanned-fast condition: one subject was not able to stop within one step of receiving the stop signal during any of the 14 unplanned-fast trials he completed (this subject's data were also excluded from the kinematic analyses) and the other 3 did not stop cleanly on a force plate during any of unplanned-fast trials (these data were included in kinematic analyses). Therefore, kinematic comparisons included a total of 12 subjects, while kinetic comparisons included a total of 9 subjects.

Subjects took approximately 1 s to stop after receiving the stop signal, regardless of the speed at which they were walking (Table 1). Subjects had a higher success rate of stopping within one step during preferred speed trials, compared to fast speed trials. Approach velocities for all trials are also included in Table 1. These results show that walking velocity was similar during planned and unplanned stopping and that subjects maintained the target velocity until the last step during planned stopping tasks. Step length was longer during walking than during the stop step, though these steps were of similar lengths in the unplanned fast condition.

Table 1. Approach velocity (average forward velocity of 30 frames prior to penultimate foot contact) for all stopping tasks. Success rates and time to stop are reported for the UP and UF stopping tasks.

	Unplanned	
	Preferred speed (n = 14)	**Fast speed (n = 12)**
Approach velocity (m/s)	1.19 ± 0.142	1.80 ± 0.139
Approach velocity (normalized by Froude number)	0.33 ± 0.022	0.51 ± 0.011
Successful one step stop trials (average)	93.8 ± 9.33%	73.7 ± 20.9%
Range of success rate for one step stopping	68.8%–100%	41.7%–100%

	Unplanned	
	Preferred speed (n = 14)	**Fast speed (n = 12)**
Time to stop (s)	1.06 ± 0.07	1.15 ± 0.10
Walking step length (normalized by leg length)	83.7 ± 5.81	100.8 ± 8.74
Stop step length (normalized by leg length)	70.8 ± 8.78	99.6 ± 12.7
	Planned	
	Preferred Speed	Fast Speed
Approach velocity (m/s)	1.23 ± 0.121	1.87 ± 0.214
Approach velocity (normalized by Froude number)	0.35 ± 0.014	0.53 ± 0.017
Walking step length (normalized by leg length)	84.4 ± 6.66	103.4 ± 6.23
Stop step length (normalized by leg length)	73.2 ± 11.6	90.6 ± 14.4

For both planned and unplanned stopping tasks, peak knee and hip flexion angles and peak knee extension moments were significantly greater during fast walking trials compared to the preferred speed trials (Tables 2 and 3) ($p < 0.01$). In addition to the peak angles at these joints, there were also differences in joint angles throughout the rest of the stop stance phase (Fig. 2). Although no statistical analyses were run using the walking data, the magnitude and timing of the peak angles and moments from preferred speed walking trials are included in Table 4 for context and comparison.

Table 2. Peak joint angle and internal joint moment data for the leading leg (non-dominant) from the stop step during unplanned preferred and unplanned fast trials. The timing of the peaks is reported as well. *Denotes significant difference from slower speed condition.

	Unplanned preferred	**Unplanned fast**	**p-value**	**Unplanned preferred (% stance)**	**Unplanned fast (% stance)**	**p-value**
Peak knee flexion angle (degrees) (n = 12)	34.5 ± 10.0	50.9 ± 8.20*	0.000	30.0 ± 8.41	27.1 ± 9.90	0.381
Peak hip flexion angle (degrees) (n = 12)	30.4 ± 7.03	46.0 ± 9.28*	0.000	28.0 ± 15.9	32.1 ± 24.4	0.816
Peak ankle plantarflexion moment (Nm/kg*m) (n = 9)	0.604 ± 0.110	0.591 ± 0.154	0.998	33.4 ± 14.3	30.0 ± 14.9	0.800
Peak knee extension moment (Nm/kg*m) (n = 9)	0.216 ± 0.280	0.879 ± 0.292*	0.000	22.4 ± 5.73	16.5 ± 2.27*	0.002

	Unplanned preferred	Unplanned fast	p-value	Unplanned preferred (% stance)	Unplanned fast (% stance)	p-value
Peak hip extension moment (Nm/kg*m) (n = 9)	0.432 ± 0.112	0.560 ± 0.110*	0.049	15.4 ± 18.1	10.9 ± 16.4	0.313

Table 3. Peak joint angle and internal joint moment data for the leading leg (non-dominant) from the stop step during planned preferred and planned fast trials. The timing of the peaks is reported as well. *Denotes a significant difference from slower speed condition.

	Planned preferred	Planned fast	p-value	Planned preferred (% stance)	Planned fast (% stance)	p-value
Peak knee flexion angle (degrees) (n = 12)	22.7 ± 8.78	38.5 ± 9.87*	0.000	21.2 ± 3.05	17.6 ± 2.82	0.218
Peak hip flexion angle (degrees) (n = 12)	22.8 ± 6.13	30.5 ± 7.96*	0.009	8.81 ± 4.04	11.7 ± 3.28	0.922
Peak ankle plantarflexion moment (Nm/kg*m) (n = 9)	0.432 ± 0.137	0.570 ± 0.119	0.421	44.0 ± 8.01	25.9 ± 9.78*	0.008
Peak knee extension moment (Nm/kg*m) (n = 9)	0.240 ± 0.177	0.810 ± 0.403*	0.001	16.4 ± 4.08	13.3 ± 2.16*	0.030
Peak hip extension moment (Nm/kg*m) (n = 9)	0.236 ± 0.076	0.528 ± 0.146*	0.000	6.30 ± 4.88	4.34 ± 2.47	0.848

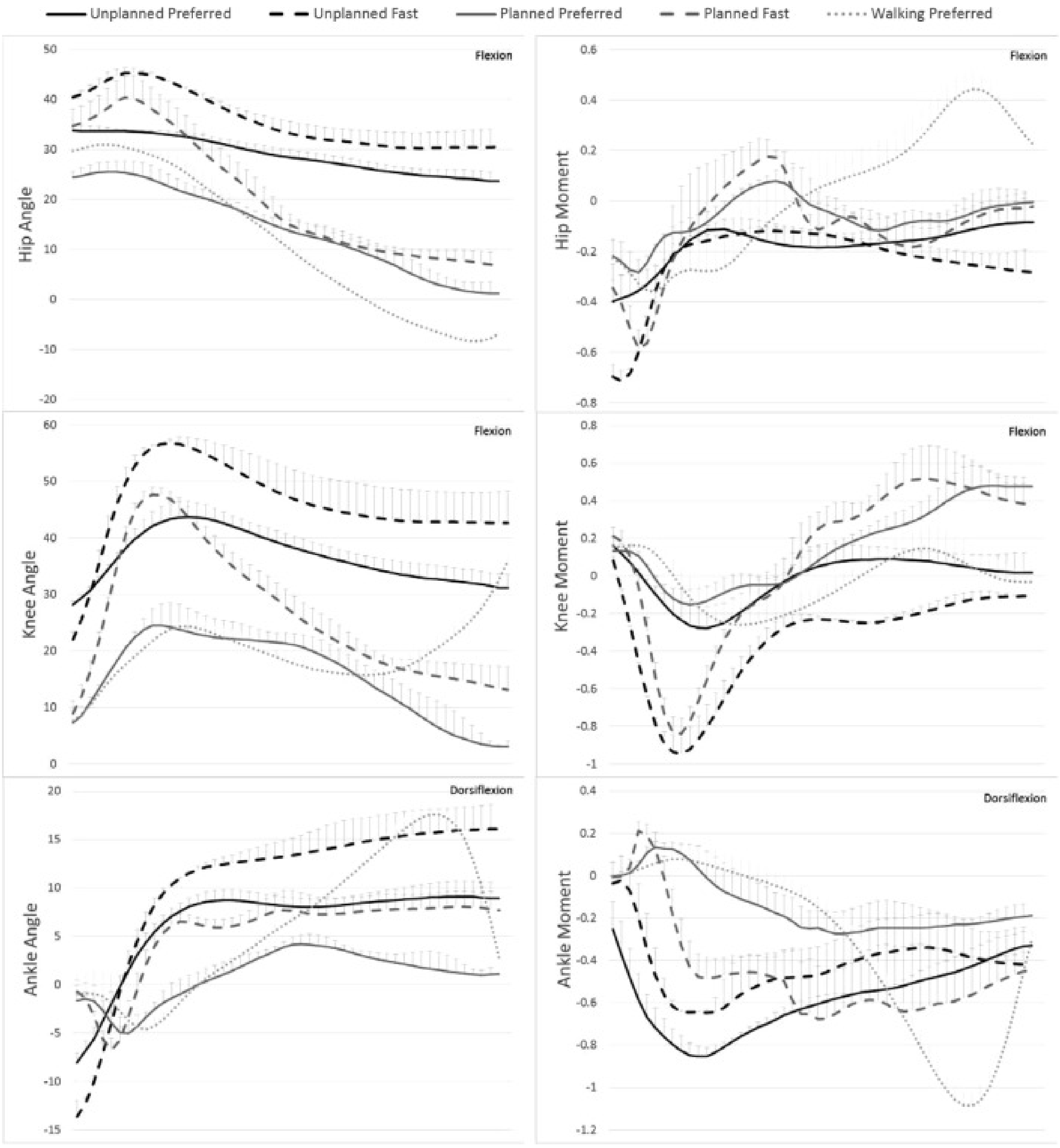

Fig. 2. Representative joint angles and internal joint moments during the stop stance phase for the lead leg during all stopping conditions and stance phase during preferred speed walking. Graphs show data for each condition for a representative subject. The start of the graph represents terminal foot contact (or foot contact, for walking), while the end represents stable stop position (or toe-off, for walking). Data from each stance phase was time normalized for comparison.

Table 4. Peak joint angle and internal joint moment data for the non-dominant leg from the preferred speed walking trials. The timing of the peaks is reported as well.

	Walk preferred	**Walk preferred (% stance)**
Peak knee flexion angle (degrees) (n = 12)	24.6 ± 7.83	28.3 ± 5.46
Peak hip flexion angle (degrees) (n = 12)	26.3 ± 4.90	8.98 ± 4.50
Peak ankle plantarflexion moment (Nm/kg*m) (n = 9)	0.788 ± 0.159	82.6 ± 5.30
Peak knee extension moment (Nm/kg*m) (n = 9)	0.346 ± 0.175	28.8 ± 6.99
Peak hip extension moment (Nm/kg*m) (n = 9)	0.291 ± 0.056	9.41 ± 4.95

Within the same test condition (planned or unplanned), all peak angles and most peak moments occurred at similar times during trials of both speeds (Tables 2 and 3). The exceptions to this were the peak ankle plantarflexion moment during planned stopping and peak knee extension moment during unplanned stopping.

4. Discussion

4.1. Preferred speed vs. fast speed comparisons

The purpose of this study was to gain a greater understanding of the differences in joint kinematics and kinetics required to perform stopping tasks during preferred speeds and faster than preferred walking speeds, for young able-bodied subjects. Most subjects were able to complete all of the tasks relatively easily; the average success rate of one-step stopping during preferred walking speeds (93.8 ± 9.33%) was similar to previously published data (93%) using young adults (ages 19–30) walking at comparable speeds (Tirosh et al., 2005). However, our subjects' average success rate during unplanned-fast trials (73.7 ± 20.9%) was slightly lower than that of subjects in the previous study (78%) walking at a comparable speed (Tirosh et al., 2005). This difference may be accounted for by the variability in the success rates of our subjects. According to feedback from some of our subjects, they felt that they were walking at their maximum speed, suggesting that the relative difficulty for those subjects was similar to that of the subjects in the previous study when completing trials at their maximum speed, which had a lower success rate of 39% (Tirosh et al., 2005). Despite the expected variability in our subjects' stopping strategies, we found several important differences in the performance of these tasks under different speed conditions.

Our analyses showed increases in peak hip and knee flexion angles and extension moments in fast walking/stopping when compared to preferred speed walking/stopping. The increases in peak hip and knee flexion angles are likely a response which allows the subject to absorb the increased ground reaction forces. The increased peak hip and knee extension moments during the fast trials were likely due to the combination of greater peak flexion angles, along with increased anterior-posterior ground reaction forces during faster walking (as found in previous research (Bishop, Brunt, Pathare, & Patel, 2004; Bishop et al., 2002, 2006; Tirosh et al., 2005)). These findings suggest that greater quadriceps, hamstring, and/or gluteal strength and power may need to be developed to assist with fast stopping (Diop et al., 2005). Some subjects also stabilized with greater knee flexion, which may contribute to faster stopping times, but may also require more knee extensor activity for stability.

Increased hip flexion was also common during fast stops when compared to the same task performed at the preferred speed. For example, during the unplanned-fast stops, most subjects (9 of 12) landed with more hip flexion than all other conditions and continued to flex through the early part of the stop stance phase, prior to extending the hip as they stabilized and stopped the forward motion of the COM (see Fig. 2). Pai and Patton (1997) suggested that a person could successfully stop at higher velocities when the COM was more posterior relative to the leading foot. This would suggest that subjects should be trained to approach stopping with an upright posture and more flexed hip during faster walking.

The earlier timing of the peak knee extension moment during faster trials is also likely related to the increased GRF necessary to stop forward progression and suggests the importance of the knee extensors. Although the magnitude of peak ankle plantarflexion moment didn’t change during the planned-fast trials when compared to planned-preferred trials, the timing of the peak was significantly later during planned-preferred trials. This change may be explained by the fact that subjects were often in slightly more dorsiflexion at foot contact during planned-preferred stops than during planned-fast stops. However, it should be noted that during all planned stopping trials, the subjects were instructed to stop and bring their feet together. This resulted in plantarflexion moments that continued to increase throughout contralateral foot contact in about one-third of the planned stopping trials used for analysis. In these cases, the peak plantarflexion moment was determined to be the plantarflexion moment at the frame prior to contralateral foot contact. This may account for some of the variability in magnitude of the peak plantarflexion moment, as well as the timing. Even considering this variability, it does not appear that manipulation of the ankle joint moment is the primary mechanism for performing gait termination, as it may be for increasing or decreasing walking speed (Orendurff, Bernatz, Schoen, & Klute, 2008).

4.2. Planned vs. unplanned comparisons

Some interesting trends can be noted when comparing variables across speed and planning conditions. The results of this study, along with results of a previous study, show that the knee joint angle is one of the prime variables of interest for this task (Serrao et al., 2013). In general, subjects exhibited less knee and hip flexion throughout the trial during planned trials than unplanned trials. However, peak knee and hip flexion angles were very similar (and not statistically significantly different) between the planned-fast and unplanned-preferred condition, suggesting there are some similarities between stopping from a higher speed and responding to an unanticipated signal to stop. Previous data has shown that ground reaction forces under the lead limb during planned stopping at increased velocities were similar to preferred speed unplanned stopping (Bishop et al., 2002, 2004). Perhaps the subjects respond to these forces in similar ways – by relying on the knee and hip more to absorb force, and control the motion of the center of mass. This data suggests that it may be possible to utilize planned stopping at faster speeds as a protocol that stresses the individual and gives clinicians an indication of how children would respond to an unexpected stimulus which required them to stop quickly. Further research using faster walking velocities and a force plate targeting protocol should be conducted to determine whether this strategy produces results similar to unplanned stopping protocols.

Clearly, the planned stopping protocols would be substantially easier to implement in some pathological populations, where response to an external stimulus may be more of an issue than with a healthy population.

4.3. Clinical application

This data from healthy youth provides normative data describing the mechanics used to perform both planned and unplanned stopping tasks. In order to determine which training and/or treatment practices may be effective for individuals who have difficulty with these tasks, it is important to understand the mechanics of unimpaired individuals.

Data from the current study suggests that strengthening of the quadriceps and hamstrings may be required to control knee motion under greater ground reaction forces found during stopping, as well as for stabilization during the stop stance phase. Research has shown that strength and resistance training is effective in children with cerebral palsy, contrary to earlier concerns about increasing spasticity (Damiano, 2009). It also appears that approaching the terminal step with a more flexed hip may help keep the center of mass posterior to the lead foot and allow for more efficient stopping. Therefore, strengthening and stretching may be aspects of gait to focus on during treatment of individuals who have difficulty with gait termination. In addition, clinicians may want to consider the potential negative influence of surgeries, such as rectus femoris transfers, that are designed to weaken the knee extensors to allow more knee flexion during swing phase. Weak knee extensors may also lead to difficulty performing gait termination. Further research is needed to determine if such surgeries do have a deleterious effect on gait termination.

5. Conclusions

This study provided evidence that stopping at faster walking velocities required lower body mechanics that differed from stopping at preferred walking velocities. Specifically, peak hip and knee flexion angles were significantly greater during the fast stopping tasks, regardless of whether the stop was planned or unplanned. Hip and knee extension moments were also greater during the faster stops. These changes may contribute to children having more difficulty with stopping quickly when they are approaching the stop at a higher velocity. This study also provides baseline data that may be useful in planning treatment and/or training for patients who have difficulty terminating gait efficiently.

References

Bishop, M., Brunt, D., & Marjama-Lyons, J. (2006). Do people with Parkinson's disease change strategy during unplanned gait termination? Neuroscience Letters, 397(3), 240–244. http://dx.doi.org/10.1016/j.neulet.2005.12.031.

Bishop, M., Brunt, D., Pathare, N., & Patel, B. (2004). The effect of velocity on the strategies used during gait termination. Gait & Posture, 20(2), 134–139. http://dx.doi.org/10.1016/j.gaitpost.2003.07.004.

Bishop, M. D., Brunt, D., Pathare, N., & Patel, B. (2002). The interaction between leading and trailing limbs during stopping in humans. Neuroscience Letters, 323(1), 1–4. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11911976.

Damiano, D. L. (2009). Rehabilitative therapies in cerebral palsy: The good, the not as good, and the possible. Journal of Child Neurology, 24(9), 1200–1204. http://dx.doi.org/10.1177/0883073809337919.

Diop, M., Rahmani, A., Belli, A., Gautheron, V., Geyssant, A., & Cottalorda, J. (2005). Influence of speed variation and age on ground reaction forces and stride parameters of children's normal gait. International Journal of Sports Medicine, 26(8), 682–687. http://dx.doi.org/10.1055/s-2004-830382.

Hof, A. L. (1996). Scaling gait data to body size. Gait & Posture, 4(3), 222–223. http://dx.doi.org/10.1016/0966-6362(95)01057-2.

Hreljac, A. (1995). Determinants of the gait transition speed during human locomotion: Kinematic factors. Journal of Biomechanics, 28(6), 669–677.

Jaeger, R. J., & Vanitchatchavan, P. (1992). Ground reaction forces during termination of human gait. Journal of Biomechanics, 25(10), 1233–1236. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1400524.

Meier, M. R., Desrosiers, J., Bourassa, P., & Blaszczyk, J. (2001). Effect of type II diabetic peripheral neuropathy on gait termination in the elderly. Diabetologia, 44(5), 585–592. http://dx.doi.org/10.1007/s001250051664.

Orendurff, M. S., Bernatz, G. C., Schoen, J. A., & Klute, G. K. (2008). Kinetic mechanisms to alter walking speed. Gait & Posture, 27(4), 603–610. http://dx.doi. org/10.1016/j.gaitpost.2007.08.004.

Pai, Y., & Patton, J. (1997). Center of mass velocity-position predictions for balance control. Journal of Biomechanics, 30(4), 347–354.

Ridge, S. T., Henley, J., Manal, K., Miller, F., & Richards, J. G. (2013). Kinematic and kinetic analysis of planned and unplanned gait termination in children. Gait and Posture, 37(2), 178–182. http://dx.doi.org/10.1016/j.gaitpost.2012.06.030. Ridge, S. T., &

Richards, J. G. (2011). Real-time feedback as a method of monitoring walking velocity during gait analysis. Gait and Posture, 34, 564–566. http://dx.doi.org/10.1016/j.gaitpost.2011.07.004.

Serrao, M., Conte, C., Casali, C., Ranavolo, A., Mari, S., Di Fabio, R., ... Pierelli, F. (2013). Sudden stopping in patients with cerebellar ataxia. Cerebellum (London, England), 12(5), 607–616. http://dx.doi.org/10.1007/s12311-013-0467-x.

Sparrow, W. A., & Tirosh, O. (2005). Gait termination: A review of experimental methods and the effects of ageing and gait pathologies. Gait & Posture, 22(4), 362–371. http://dx.doi.org/10.1016/j.gaitpost.2004.11.005.

Tirosh, O., & Sparrow, W. A. (2004). Gait termination in young and older adults: Effects of stopping stimulus probability and stimulus delay. Gait & Posture, 19(3), 243–251. http://dx.doi.org/10.1016/S0966-6362(03)00063-8.

Tirosh, O., & Sparrow, W. A. (2005). Age and walking speed effects on muscle recruitment in gait termination. Gait & Posture, 21(3), 279–288. http://dx.doi. org/10.1016/j.gaitpost.2004.03.002.

Vrieling, A. H., van Keeken, H. G., Schoppen, T., Otten, E., Halbertsma, J. P. K., Hof, A. L., et al (2008). Gait termination in lower limb amputees. Gait & Posture, 27(1), 82–90. http://dx.doi.org/10.1016/j.gaitpost.2007.02.004.

Wikstrom, E. A., Bishop, M. D., Inamdar, A. D., & Hass, C. J. (2010). Gait termination control strategies are altered in chronic ankle instability subjects. Medicine and Science in Sports and Exercise, 42(1), 197–205. http://dx.doi.org/10.1249/MSS.0b013e3181ad1e2f.

Wikstrom, E. A., & Hass, C. J. (2012). Gait termination strategies differ between those with and without ankle instability. Clinical Biomechanics (Bristol, Avon), 27(6), 619–624. http://dx.doi.org/10.1016/j.clinbiomech.2012.01.001.