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original research

Muscle Activation and Movement Patterns During Prone Hip Extension Exercise in Women

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Context: The consistency of muscle activation order during prone hip extension has been debated.

Objective: To investigate whether women use a consistent and distinguishable muscle activation order when extending the hip while prone and to explore the effects of verbal cues on muscle activation and movement.

Design: Single-session, repeated-measures design.

Setting: University laboratory.

Patients or Other Participants: Eleven healthy women (age = 27.7 ± 6.2 years [range, 22–37 years]).

Intervention(s): We tested the participants under 3 conditions: no cues, cues to contract the gluteal muscles, and cues to contract the hamstrings muscles.

Main Outcome Measure(s): We measured hip and knee angle and electromyographic data from the gluteus maximus, medial hamstrings, and lateral hamstrings while participants performed prone hip extension from 30° of hip flexion to neutral.

Results: When not given cues, participants used the consistent and distinguishable muscle activation order of medial hamstrings, followed by lateral hamstrings, then gluteus maximus (195.5 ± 74.9, 100.2 ± 70.3, and 11.5 ± 81.9 milliseconds preceding start of movement, respectively). Compared with the no-cues condition, the gluteal-cues condition resulted in nearly simultaneous onset of medial hamstrings, lateral hamstrings, and gluteus maximus (131.3 ± 84.0, 38.8 ± 96.9, and 45.1 ± 93.4 milliseconds, respectively) ($P > .059$); decreased activation of the medial hamstrings ($P < .03$) and lateral hamstrings ($P < .024$) around the initiation of movement; increased activation of gluteus maximus throughout the movement ($P < .001$); and decreased knee flexion ($P = .002$). Compared with the no-cues condition, the hamstrings-cues condition resulted in decreased activation of the medial hamstrings just after the initiation of movement ($P = .028$) and throughout the movement ($P = .034$) and resulted in decreased knee flexion ($P = .003$).

Conclusions: Our results support the contention that the muscle activation order during prone hip extension is consistent in healthy women and demonstrates that muscle timing and activation amplitude and movement can be modified with verbal cues. This information is important for clinicians using prone hip extension as either an evaluation tool or a rehabilitation exercise.

Key Words: electromyography, motor control, verbal cues

Key Points

- Women used a consistent order of muscle contraction during prone hip extension that began with the medial hamstrings, was followed by the lateral hamstrings, and concluded with the gluteus maximus.
- When compared with the no-cues condition, verbal cues to contract the gluteal muscles while lifting the leg resulted in nearly simultaneous contraction of the hamstrings and gluteus maximus, stronger activation of the gluteus maximus, and reduction of total knee flexion.
- Our findings are clinically important because they establish the normal activation pattern during prone hip extension and indicate that changes in knee flexion while performing prone hip extension may indicate altered muscle activity.

Evaluation of the muscle activation pattern during prone hip extension has been proposed as a clinical tool for assessment of musculoskeletal dysfunction. Early activation of the spinal erector and hamstrings muscles and decreased or delayed activation of the gluteal muscles has been interpreted as an indication of faulty muscle activation.[1,2] Additionally, excessive knee flexion has been suggested as a sign of hamstrings overactivity.[3,4] Investigators[2,5] have also reported that activation of the hamstrings muscles earlier than the gluteal muscles contributes to hip dysfunction and anterior hip pain[2] because the pattern increases anterior joint forces.[5] Correction of the faulty pattern is recommended to reduce the stress on the hip joint and spine.[1,2] Providing verbal cues for specific muscle recruitment is one method for modifying muscle activity.

In many rehabilitation textbooks, researchers have advocated the use of prone hip extension to evaluate muscle activation[1–4,6,7]; however, the existence of a consistent activation pattern during prone hip extension is still debated. Some investigators have reported a consistent pattern, beginning with the hamstrings muscle and ending with the gluteus maximus muscle.[8,9] However, other investigators[10,11] have concluded that no pattern exists. Possible explanations for the differences in conclusions include methodologic issues, such as number of muscles evaluated, how the exercise was performed, and the sex of the participants included in the study.

The primary purpose of our study was to determine if women without hip or back pain used a consistent order of activation among the gluteus maximus, medial hamstrings, and lateral hamstrings muscles during prone hip extension. We hypothesized that women would demonstrate a consistent order of muscle activation and that the order would begin either with contraction of the gluteus maximus muscle alone or with simultaneous contraction of the gluteus maximus and the hamstrings muscles.

A secondary interest of the study was to investigate if verbal cues would affect the timing or amplitude of muscle activation or the kinematics of movement. We hypothesized that verbal cues to contract the gluteal muscles while keeping the hamstrings muscles relaxed would result in earlier and stronger activation of the gluteal muscles and reduced knee flexion when compared with the no-cues condition.

METHODS

Participants

Eleven women (age = 27.7 ± 6.2 years [range, 22–37 years], height = 165.2 ± 3.6 cm [range, 161–173 cm], mass = 62.3 ± 6.9 kg [range, 54–78 kg]) were recruited from community sources. Based on data reported by Lehman et al,[11] 11 participants were sufficient for detecting differences in muscle activation onset times with an α level set at .05. All participants gave written informed consent, and the study was approved by each university's institutional review board before testing. Exclusion criteria for the participants included (1) history of hip or back pain lasting more than 1 week within the 5 years before testing, (2) current lower extremity injury, (3) hip pain with active straight-leg raises or passive hip flexion with adduction and medial rotation, or (4) history of a central nervous system or neuromuscular disorder.

Instrumentation

We used a 6-camera, 3-dimensional motion capture system (Motion Analysis Corp, Santa Rosa, CA) to collect kinematic data. The sampling rate of each camera was 60 Hz, and the static resolution of the entire system was 1 mm for a volume of 1 m^3. We used a standard retroreflective marker set (Helen Hayes Hospital, West Haverstraw, NY).[12] Markers were placed bilaterally between the heads of the second and third metatarsals, on the posterior aspect of the calcaneus, on the medial and lateral malleoli, on the medial and lateral knee joint lines, and on the anterior-superior iliac spines. A stick with a marker attached to the end was placed on the sacrum and secured with tape. Similar sticks with markers were placed on the shank and thigh bilaterally and were secured with an elastic band. An additional marker was placed on each iliac crest for reconstruction of the location of the anterior-superior iliac spine markers, which were removed when the participant was positioned prone.

Surface electromyographic (EMG) data were recorded at 1200 Hz and bandpass filtered during data collection at 10 to 500 Hz using Myosystem 1400A (Noraxon USA Inc, Scottsdale, AZ). To record muscle activity, we used bipolar, disposable, self-adhesive, Ag/AgCl surface electrodes (Noraxon USA Inc) that were 1 cm in diameter and had an interelectrode distance of 2 cm. The surface electrodes were placed over the muscle bellies of the gluteus maximus, medial hamstrings (semimembranosus and semitendinosus), and lateral hamstrings (biceps femoris) muscles according to guidelines for surface electrode placement.[13] A ground electrode was placed on the lateral aspect of the iliac crest. We wrapped the area with 3 layers of prewrap (Cramer Products Inc, Gardner, KS) to hold the electrodes in place and reduce movement artifact.

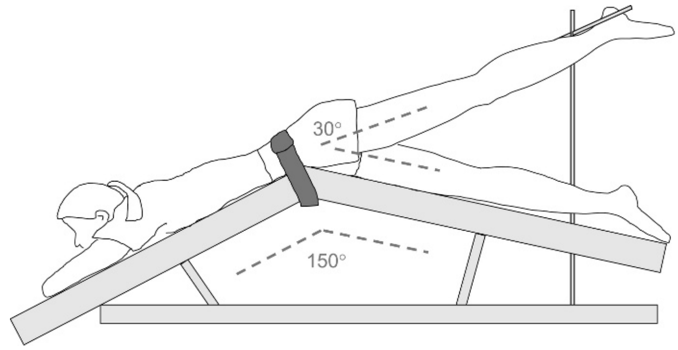

Figure 1. Participant positioning during testing. The table was adjusted so that the participant's hips were in approximately 30° of hip flexion. An adjustable bar was placed over the participant's legs and positioned so that her Achilles tendon would contact the bar when the hip was in approximately 0° of extension.

Experimental Procedures

For each participant, a limited musculoskeletal examination of the lower extremities was performed by a clinician (C.L.L.). The examination included passive range-of-motion measurements and active and passive movement tests. Of particular importance to this study, 2 specific movements were performed in supine position to screen participants for hip pain. The first movement was active hip flexion with the knee maintained in extension (straight-leg raises). The second movement was passive hip flexion with adduction, medial rotation, and slight overpressure. During both of these movements, participants were instructed to rate their pain on an 11-point numerical rating scale, with larger numbers indicating greater pain intensity.[14] Participants were excluded if they reported hip pain greater than 0 with either of these tests. We used active straight-leg raising and passive hip flexion with adduction and medial rotation as screening tests because patients with hip joint disorders commonly report pain with these provocative movements.[15–19]

After placing the EMG electrodes and retroreflective markers on the participant, we collected data on a static standing trial. We used OrthoTrak software (Motion Analysis Corp) to locate the joint centers from this static trial. After static trial data collection, the anterior-superior iliac spine, medial malleolus, and medial knee joint line markers were removed.

Each participant was positioned prone on an adjustable table that consisted of 2 segments joined at a 150° angle (Figure 1). This table configuration allowed the participant's hips to be positioned initially in approximately 30° of hip flexion, as verified by the clinician using a standard plastic goniometer. A moveable bar was placed over the table in alignment with the distal part of the leg, so that the Achilles tendon would contact the bar when the hip was extended to neutral. A belt was used to secure the participant's pelvis to the table and, thus, stabilize the back and pelvis to confine movement to the hip joint. We recorded EMG data during a 10-second resting trial in which the participant was instructed to relax completely. This resting trial was used as the baseline reference in determining muscle activation onsets. Next, the participant was instructed to maintain the knee in extension while lifting the leg from the table to contact the adjustable bar and returning the leg to the table. A piece of medical tape that was approximately 2-ft (0.61-m) long was placed along the anterior aspect of the participant's leg, crossing the knee joint while the knee was in extension. The tape served as a tactile cue to remind the participant not to flex the knee. To maintain consistency for each participant, we used the tactile cue from the tape rather than the verbal cues as would be used in the clinic. A metronome set to 60 beats per minute was used to help regulate the rate of the movement at approximately 30° per second. Participants performed at least 4 repetitions of the movement with a 2-second rest period between repetitions.

After the prone hip extension trials were completed, we collected the EMG activity during maximal voluntary isometric contraction (MVIC) trials in which maximal manual resistance was applied to each muscle group. For these MVIC tests, we used standard manual muscle testing techniques.[20] Specifically, the gluteus maximus muscle was tested with the hip extended, the knee flexed to at least 90°, and resistance applied to the distal aspect of the posterior portion of the thigh. The hamstrings muscles were tested with the thigh resting on the table, the knee flexed to approximately 20°, and resistance applied to the distal aspect of the posterior portion of the shank. Participants performed a single repetition and held contractions for at least 1 second. The MVIC was calculated as the average rectified EMG over a 30-millisecond period surrounding the maximum activity. To avoid artificially inflating the MVIC, we used an average value surrounding the maximum activity instead of the value of the maximum activity. We used this MVIC value to normalize muscle activity.

Conditions

To test whether women activated muscles in a consistent order, the first condition was performed by the participant without any verbal cues regarding which muscles to use to extend the hip (no-cues condition). To investigate if verbal cues might affect muscle activation, we used 2 other conditions in which we gave the participant verbal cues to activate a specific muscle group. For the gluteal (glut)-cues condition, the participant was instructed: "Use your gluteal muscles to lift your leg while keeping your hamstrings muscles relaxed." For the hamstrings (HS)-cues condition, the participant was instructed: "Use your hamstrings muscles to lift your leg while keeping your gluteal muscles relaxed." For both cued conditions, the participants were given the instructions before performing a set of at least 4 repetitions. All participants were aware of surface anatomy, but, while giving instructions, we identified the gluteus maximus and hamstrings muscles by palpation to ensure that they understood which muscles to activate. Participants were not aware of the specific hypotheses being tested. No cues were given during the set of repetitions. Participants were allowed up to 2 practice trials under each condition, but no feedback was given during these trials. The no-cues condition was always performed first to avoid any effect associated with the verbal cues used in the other conditions. The order of the cued conditions was randomized.

Data Processing

Kinematics. Three-dimensional marker trajectories were obtained using a real-time tracking system (EVaRT version 4.0; Motion Analysis Corp). Kinematic data were smoothed using a 6-Hz Butterworth filter (EVaRT). OrthoTrak was used to locate joint centers and record the hip and knee angles for each frame of kinematic data. The recorded joint kinematics were exported as ASCII files and imported into MATLAB (The MathWorks, Natick, MA) to perform further calculations and identify the minimum and maximum values for the variables being studied.

Kinematic Variables. The primary kinematic variable of interest was the start of the hip extension motion. We defined the start of movement as the first time that the hip extension displacement within a frame exceeded 0.04° and was maintained for 100 milliseconds (6 frames), which was determined by a MATLAB program developed for this study. This displacement threshold was equal to a velocity of 2.4° per second and occurred approximately when the frame displacement exceeded 5% of the maximum frame displacement for the trials. We used the start-of-movement frame as a zero reference point, similar to the methods of Bullock-Saxton.[21] Specifically, we adjusted all other timing variables to this reference point. Muscle activity that began before the start of movement was given positive onset time values, and muscle activity beginning after the start of movement was given negative onset time values.

Because increased knee flexion during prone hip extension is thought to indicate hamstrings overactivity, we also investigated the kinematics of the movement and whether verbal cues changed the movement. To do this, we calculated the total knee excursion from the start of the hip extension movement until the end of movement. The end of the hip extension movement was defined as the frame in which the maximum hip extension angle was achieved during that repetition.

Electromyography. The raw EMG data were extracted from the binary EVaRT files by a custom-written C++ program. Any offset in the EMG channels (oscillation about a point other than zero) was corrected to within 0.1%. The corrected data were then imported into the MATLAB program developed for this study that accounted for the difference in sampling rate (60 Hz for kinematic and 1200 Hz for EMG).

Electromyographic Variables. To test whether women used a consistent and distinguishable order of muscle activation, we examined the onset timing of the gluteus maximus, lateral hamstrings, and medial hamstrings muscles relative to the start of movement. The EMG data were smoothed using a zero-phase lag, digital, fourth-order, low-pass Butterworth filter at 10 Hz.[22] We defined *on* as the time at which the EMG activity of the muscle exceeded its mean from the resting trial by 3 SDs[23,24] and maintained that activity for at least 75 milliseconds (Figure 2). Onset times were first identified using a custom-written MATLAB program. As is recommended when using computerized algorithms to determine onset times, the EMG data and the muscle onset times were graphed for visual confirmation.[25,26] Modification of the computer-determined muscle onset times was performed in a blinded manner and in less than 12% of the repetitions.

To evaluate the effect of cues on the amount of muscle activity, we assessed the amplitude of muscle activation around the start of the movement and over the course of the movement. Within each of 8 50-millisecond epochs, we averaged the amplitude of the bandpass filtered and rectified EMG as a percentage of the MVIC. Four epochs occurred immediately before the start of movement, and 4 epochs

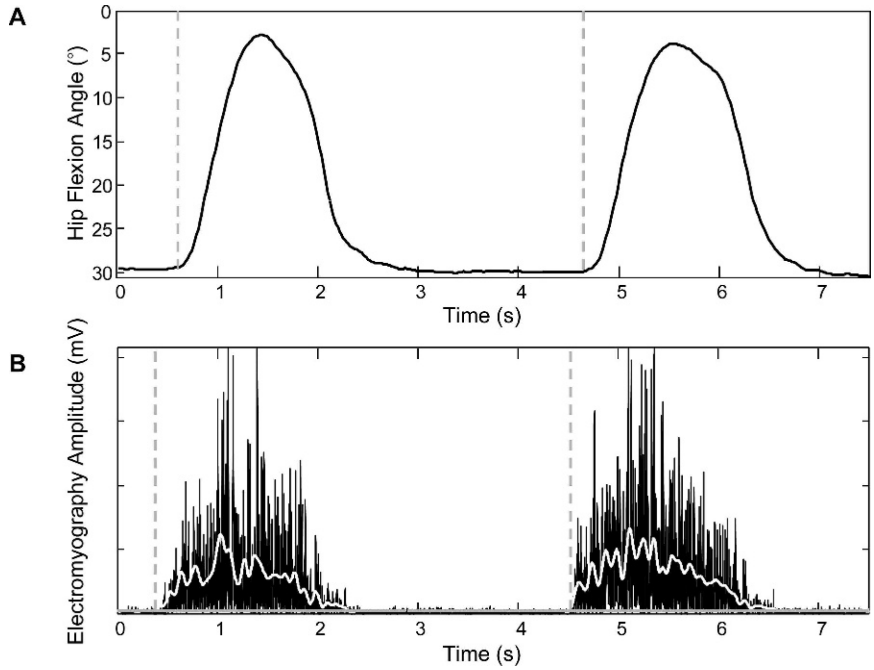

Figure 2. A, The start of the hip extension movement (dashed gray vertical line) was defined as the frame in which the frame displacement exceeded 0.04° and was maintained for 100 milliseconds. B, The raw electromyographic (EMG) data were rectified (thin black line) and low-pass filtered at 10 Hz (thick white line). The muscle onset (dashed gray vertical line) was defined as the point at which the EMG activity of the muscle exceeded the resting mean by 3 SDs (thick gray horizontal line) and maintained that activity for at least 75 milliseconds. Two repetitions of prone hip extension are displayed from a representative participant during the no-cues condition.

occurred immediately after the start of movement (Figure 3). Averaging the EMG data within epochs allowed us to evaluate not only the onset time of each muscle but also the quantity of muscle activation at the initiation of hip extension.[27] We also calculated the average amplitude of the EMG activity from the start of movement to the end of movement as an indication of the quantity of activation throughout the movement.

Data Analysis

Each participant performed at least 4 trials of hip extension under each condition. We averaged the first 4 trials together to produce a single mean value for each variable under each condition. We describe the analysis of the mean values for each variable.

Order of Muscle Activation. We used a Friedman 2-way analysis of variance (ANOVA) to test the null hypothesis of no systematic order of activation among the gluteus maximus, medial hamstrings, and lateral hamstrings muscles during the no-cues condition. The Friedman ANOVA is a nonparametric statistic specifically for rank analysis. In addition to testing for a consistent order of activation, we also used paired *t* tests to determine if the muscle onsets were distinguishable from one another.

Effect of Cues on Order of Muscle Activation. As with the no-cues condition, we used the nonparametric Friedman ANOVA to determine if muscles were activated in a consistent order and used paired *t* tests to determine if the muscle onsets were distinguishable from one another. Separate analyses were used to evaluate each condition.

Effect of Cues on Muscle Timing. A repeated-measures ANOVA with 2 factors was used to test for changes in each muscle's timing between the conditions. We conducted this analysis separate from testing muscle order because order of onset could be consistent, but the actual timing of each muscle could be highly variable. The factors were muscle (gluteus maximus, medial hamstrings, lateral hamstrings) and condition (no cues, glut cues, HS cues). The dependent variable was the muscle onset time.

Effect of Cues on Amplitude. To test the effect of cues on the amplitude of muscle activation at initiation and throughout the movement, we used separate repeated-measures ANOVAs for each muscle. For the amplitude at initiation of hip extension, the 2 factors were epoch (1–8) and condition (no cues, glut cues, HS cues). The dependent variable was the average amplitude of muscle activity as a percentage of MVIC for each epoch. To compare muscle activation throughout the movement, the factor was condition (no cues, glut cues, HS cues), and the dependent variable was the average amplitude of muscle activity as a percentage of MVIC from initiation to the end of movement.

Effect of Cues on Movement. To test the effect of cues on knee movement, we used a repeated-measures ANOVA. The factor was condition (no cues, glut cues, HS cues), and the dependent variable was the total knee excursion.

All statistical analyses were performed in SYSTAT 11 (SYSTAT Software Inc, Chicago, IL). The α level was set a priori at .05. All levels of the repeated-measures ANOVA that resulted in significant findings were further investigated using 2-tailed paired *t* tests with Bonferroni correction.

RESULTS

Order of Muscle Activation

We found that all participants displayed a consistent order of muscle activation when performing prone hip extension

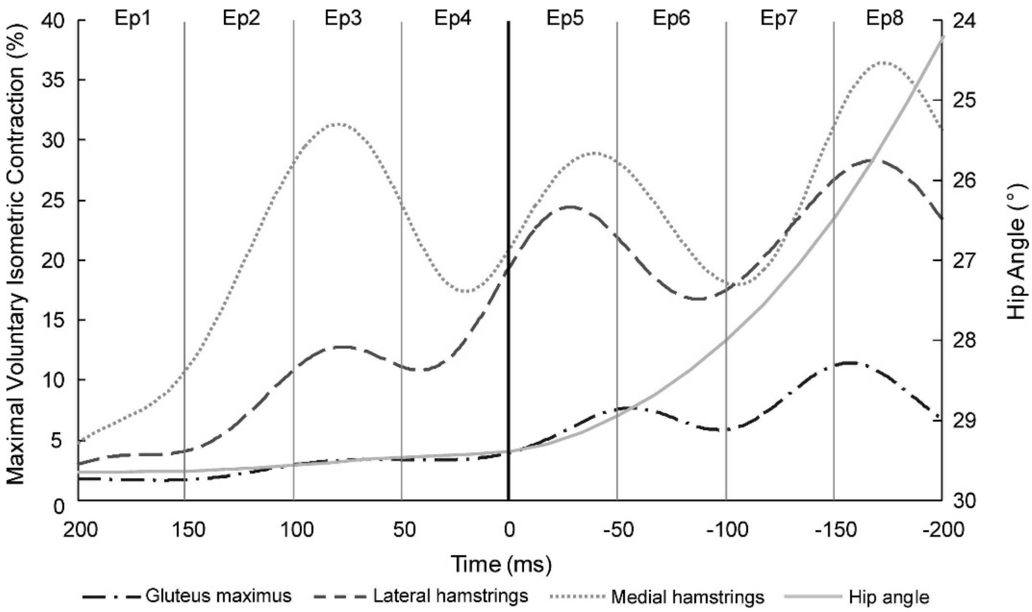

Figure 3. Representation of hip angle, rectified and smoothed electromyographic (EMG) data, and epochs (Eps 1–8) of a single participant during the no-cues condition. The 0 point of the x axis represents the start of the hip extension movement. All time points before the start of movement are positive, and time points after the start of movement are negative. The y axis on the right side is hip angle, and the y axis on the left side is EMG as a percentage of the maximal voluntary isometric contraction. The solid curve is the hip angle trace. The dotted and dashed curves represent the EMG of the gluteus maximus, lateral hamstrings, and medial hamstrings muscles. Each vertical line represents a 50-millisecond Ep. There are 4 Eps immediately before and 4 Eps immediately after the start of movement.

without verbal cues ($P = .002$). The medial hamstrings muscles were activated first (195.5 ± 74.9 milliseconds before the start of movement). The lateral hamstrings muscle was activated second (100.2 ± 70.3 milliseconds). The gluteus maximus muscle was activated third (11.5 ± 81.9 milliseconds). The activation of the medial hamstrings muscles was distinct from the activation of the gluteus maximus muscle ($P = .003$) and the lateral hamstrings muscle ($P = .006$). The gluteus maximus muscle activation was different, but not significantly, from the lateral hamstrings muscle activation ($P = .057$) (Table 1, Figure 4).

Effect of Cues on Order of Muscle Activation

During the glut-cues condition, participants maintained a consistent order ($P = .035$), yet they altered their relative muscle activation so that muscle onset times were not different among any of the 3 muscles ($P > .059$). When given HS cues, participants continued to use the consistent order of muscle activation of medial hamstrings muscles, lateral hamstrings muscle, and gluteus maximus muscle that they used in the no-cues condition. However, participants altered the relative timing, so that the gluteus maximus was distinguishable from both hamstrings muscles ($P < .015$), but the medial and lateral hamstrings muscles were not distinguishable from each other ($P = .09$) (Figure 4).

Effect of Cues on Muscle Timing

When given verbal cues, participants modified the timing of their muscle activations compared with muscle activations in the no-cues condition. We found a main effect of

Table 1. Muscle Onset Time, Average Muscle Activation Amplitude Throughout the Movement, and Total Joint Excursion for Each Condition

	Condition					
	Gluteal Cues		No Cues		Hamstrings Cues	
Variable	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval
Muscle onset, ms						
Gluteus maximus	45.1 ± 93.4	−11.3, 101.4	11.5 ± 81.9	−37.9, 60.8	−12.0 ± 89.5	−66.0, 41.9
Lateral hamstrings	38.8 ± 96.9	−19.6, 97.3	100.2 ± 70.3	57.8, 142.6	117.7 ± 86.3	65.6, 169.7
Medial hamstrings	131.3 ± 84.0	80.6, 181.9	195.5 ± 74.9	150.4, 240.7	176.0 ± 91.4	121.0, 231.1
Muscle amplitude, %MVIC						
Gluteus maximus	21.6 ± 9.8	15.8, 27.5	9.7 ± 2.9	7.9, 11.5	11.2 ± 5.2	8.1, 14.4
Lateral hamstrings	30.5 ± 15.1	21.4, 39.6	36.3 ± 7.8	31.6, 41.0	33.0 ± 11.3	26.2, 39.8
Medial hamstrings	27.9 ± 10.7	21.5, 34.4	31.2 ± 9.4	25.6, 36.9	28.8 ± 10.1	22.7, 34.9
Joint excursion, °						
Knee flexion	2.2 ± 3.1	0.3, 4.1	9.0 ± 4.5	6.3, 11.7	6.0 ± 3.9	3.7, 8.4

Abbreviation: %MVIC, percentage maximal voluntary isometric contraction.

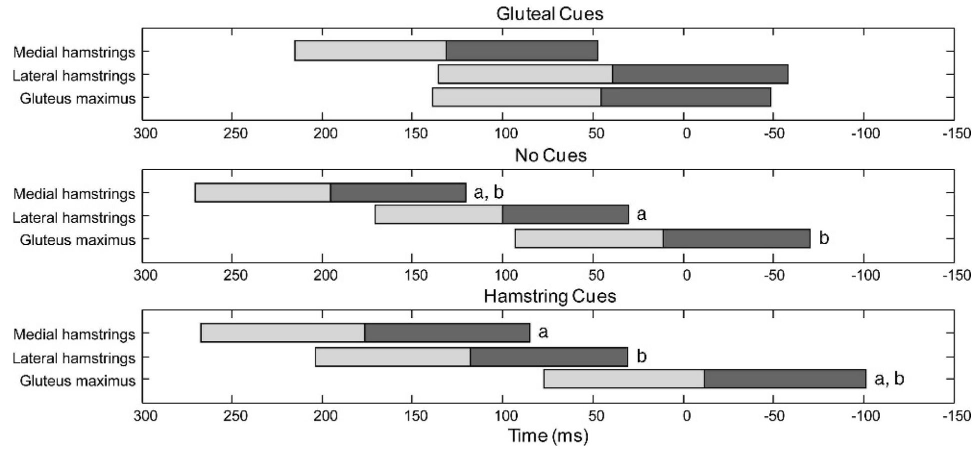

Figure 4. Evaluation of relative muscle onset times within each of the gluteal-cues, no-cues, and hamstrings-cues conditions. The vertical center line within each bar indicates mean onset time, and bars indicate 1 SD. In the no-cues condition, the onset of medial hamstrings activation (MHS) is distinguishable from the onset of the lateral hamstrings (LHS) and gluteus maximus (GM) activation, and in the hamstrings-cues condition, the onset of GM activation is distinguishable from the onset of the LHS and MHS. [a,b] Indicates difference from other muscle with the same superscript letter ($P < .05$). In the gluteal-cues condition, activation onsets were not distinguishable from one another.

muscle ($F_{2,20} = 17.391$, $P < .001$) and an interaction between muscle and condition ($F_{4,40} = 3.771$, $P = .011$), indicating that the cues affected the muscles differently. In the glut-cues condition, the activation onset of the lateral hamstrings muscle was 61.4 milliseconds closer to the start of movement compared with that muscle's timing in the no-cues condition ($P = .04$) (Figure 5). We found no change in the onset timing of the gluteus maximus or medial hamstrings muscles compared with those muscles' timing in the no-cues condition ($P > .16$). The HS-cues condition did not result in a change in the timing of any of the 3 muscles examined when compared with their timing in the no-cues condition ($P > .57$).

Effect of Cues on Amplitude at Initiation

When given verbal cues, participants modified the degree of muscle activation at the initiation of movement (Table 2). For each muscle, we found a main effect of epoch ($P < .001$).[a] For the hamstrings muscles, we also found a main effect of condition ($P < .018$)[b] and an interaction between epoch and condition ($P < .001$).[c] The activation of the lateral hamstrings muscle was lower during the glut-cues condition than during the no-cues condition for epochs 4 through 8 ($P < .024$) (Figure 6). Similarly, the activation of the medial hamstrings muscles was lower during the glut-cues condition than during the no-cues condition for epochs 3 through 8 ($P < .03$). The activation of the medial hamstrings muscles was lower in epoch 8 during the HS-cues condition than during the no-cues condition ($P = .028$).

Effect of Cues on Amplitude Throughout the Movement

When given verbal cues, participants also modified their average muscle activation throughout the movement (Table 1). We found a main effect of muscle ($F_{2,20} = 22.12$, $P < .001$) and an interaction between muscle and condition ($F_{4,40} = 6.61$, $P < .001$). The average gluteus maximus muscle activation was increased during the glut-cues condition to 21.6% of MVIC compared with 9.7% of MVIC in the no-cues condition ($P < .001$) (Figure 7). The medial hamstrings muscles decreased their average activation during the HS-cues condition to 28.8% of MVIC compared with 31.2% in the no-cues condition ($P = .034$). The average muscle activation of the lateral hamstrings muscle did not change when the participant was given verbal cues.

Effect of Cues on Movement

Along with changes in muscle timing and muscle amplitude, participants changed the kinematics of the movement when given verbal cues ($F_{2,20} = 21.85$, $P < .001$) (Table 1). When compared with the no-cues condition, participants reduced the total knee flexion excursion by 6.8° in the glut-cues condition ($P = .002$) (Figure 8). Participants also decreased total knee flexion by 2.9° in the HS-cues condition compared with the no-cues condition ($P = .003$).

DISCUSSION

Based on the results of our study, women without hip or back pain appear to have a consistent and distinguishable order of hip extensor muscle activation when performing prone hip extension without verbal cues. The order begins with the medial hamstrings muscles, is followed by the lateral hamstrings muscles, and concludes with the gluteus maximus muscle. The timing and amplitude of muscle activation, as well as the knee excursion, can be modified by verbal cues to use the gluteal muscles to lift the leg while keeping the hamstrings muscles relaxed. In the glut-cues condition, the relative timing of the muscle activation changed so that the activation onsets of the 3 muscles were indistinguishable from one another. When compared with the no-cues

[a] Main effect of epoch for gluteus maximus ($F_{7,70} = 28.5$, $P < .001$), lateral hamstrings ($F_{7,70} = 46.4$, $P < .001$), and medial hamstrings ($F_{7,70} = 39.4$, $P < .001$).
[b] Main effect of condition for lateral hamstrings ($F_{2,20} = 5.99$, $P = .009$) and medial hamstrings ($F_{2,20} = 9.02$, $P = .002$).
[c] Interaction between epoch and condition for lateral hamstrings ($F_{14,140} = 5.64$, $P < .001$) and medial hamstrings ($F_{14,140} = 3.94$, $P < .001$).

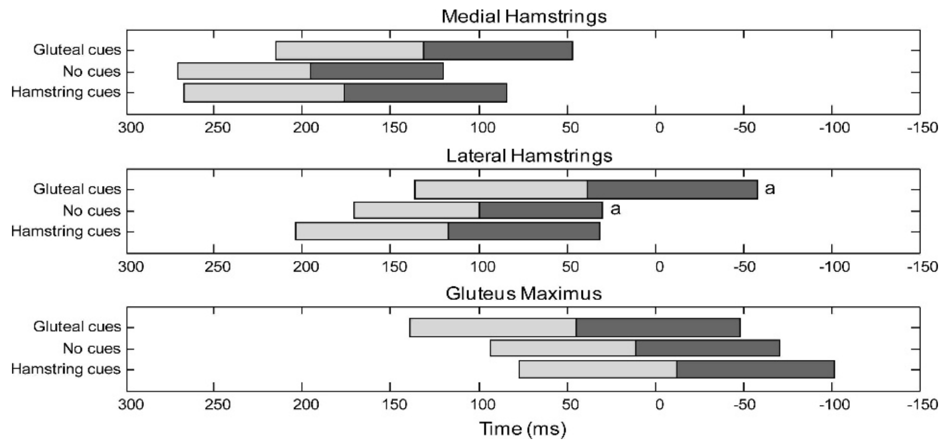

Figure 5. Evaluation of onset times for the medial hamstrings, lateral hamstrings, and gluteus maximus muscles across each condition. The vertical center line within each bar indicates mean activation onset time, and bars indicate 1 SD. The lateral hamstrings muscle was activated later in the gluteal-cues condition than in the no-cues condition. [a] Indicates $P = .04$.

condition, the lateral hamstrings muscle activation was delayed, the initial activation of the lateral and medial hamstrings muscles was reduced, and the activation of the gluteus maximus muscle throughout the movement was increased. The total knee flexion excursion was also lower in the glut-cues condition compared with the no-cues condition. Only the amplitude of the medial hamstrings muscles and the knee excursion were affected by verbal cues to use the hamstrings muscles to lift the leg while keeping the gluteal muscles relaxed. Activation of the medial hamstrings muscles during the eighth epoch and throughout the movement was reduced, and the total knee flexion excursion was also reduced in the HS-cues condition compared with the no-cues condition.

Order of Muscle Activation

Our finding of a consistent order of muscle activation during prone hip extension is clinically important. Alterations in muscle activation have been implicated in the development of hip and back pain.[1,2] Correction of these alterations has been the focus of intervention for people with anterior hip pain.[2] Despite multiple studies in which muscle activation during prone hip extension was examined,[8–11,21,28] the controversy regarding the existence of a normal activation pattern during prone hip extension has continued. Pierce and Lee[10] and Lehman et al[11] found no consistent pattern, whereas Vogt and Banzer[8] and Bullock-Saxton et al[9] reported a consistent pattern. We also found a

Table 2. Initial Muscle Activation Amplitude (Percentage Maximal Voluntary Isometric Contraction) During the 8 Epochs Spanning 200 Milliseconds Preceding Start of Movement Until 200 Milliseconds After the Start of Movement for Each Muscle in Each Condition

		Condition					
		Gluteal Cues		No Cues		Hamstrings Cues	
Muscle	Epoch	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval
Gluteus maximus	1	2.2 ± 0.8	1.8, 2.7	2.2 ± 1.3	1.5, 3.0	1.9 ± 1.0	1.3, 2.5
	2	2.4 ± 1.0	1.8, 3.0	2.4 ± 1.0	1.8, 3.0	2.0 ± 0.9	1.4, 2.5
	3	3.0 ± 1.6	2.0, 3.9	2.7 ± 1.2	2.0, 3.5	2.5 ± 1.1	1.8, 3.2
	4	4.0 ± 2.3	2.7, 5.4	3.4 ± 1.9	2.3, 4.5	3.2 ± 1.8	2.2, 4.3
	5	6.2 ± 4.8	3.3, 9.0	4.5 ± 2.8	2.8, 6.2	4.6 ± 2.9	2.8, 6.4
	6	8.3 ± 5.7	4.9, 11.7	6.2 ± 3.3	4.2, 8.3	6.1 ± 4.2	3.6, 8.6
	7	10.5 ± 7.5	6.0, 15.0	7.2 ± 4.4	4.6, 9.9	6.6 ± 3.6	4.4, 8.7
	8	12.6 ± 9.6	6.9, 18.4	8.9 ± 5.6	5.6, 12.3	8.3 ± 4.8	5.4, 11.2
Lateral hamstrings	1	3.3 ± 2.9	1.6, 5.1	3.0 ± 1.1	2.3, 3.7	2.9 ± 1.1	2.2, 3.5
	2	3.4 ± 3.1	1.5, 5.3	3.7 ± 2.0	2.5, 4.9	3.7 ± 1.6	2.7, 4.7
	3	5.0 ± 4.9	2.0, 7.9	6.6 ± 3.0	4.7, 8.4	6.5 ± 3.3	4.5, 8.6
	4	8.0 ± 7.2	3.6, 12.3	14.3 ± 6.5	10.3, 18.2	11.3 ± 5.8	7.9, 14.8
	5	9.6 ± 8.0	4.7, 14.4	18.5 ± 9.0	13.1, 23.9	14.7 ± 7.2	10.3, 19.1
	6	10.2 ± 8.1	5.3, 15.0	21.2 ± 7.9	16.4, 25.9	17.7 ± 9.4	12.0, 23.3
	7	13.1 ± 10.5	6.7, 19.4	23.1 ± 8.6	17.9, 28.3	18.2 ± 9.6	12.4, 24.0
	8	16.2 ± 11.2	9.4, 22.9	27.8 ± 8.1	22.9, 32.7	23.8 ± 12.3	16.4, 31.2
Medial hamstrings	1	3.5 ± 2.5	2.0, 5.0	5.1 ± 2.7	3.5, 6.8	4.3 ± 3.2	2.3, 6.2
	2	4.6 ± 3.4	2.5, 6.7	6.8 ± 4.5	4.1, 9.5	5.6 ± 3.8	3.3, 7.9
	3	6.3 ± 4.4	3.7, 9.0	11.3 ± 5.6	7.9, 14.7	8.8 ± 4.9	5.8, 11.8
	4	9.5 ± 5.5	6.2, 12.8	16.8 ± 6.1	13.1, 20.5	13.3 ± 7.2	9.0, 17.7
	5	12.6 ± 5.0	9.6, 15.5	20.9 ± 7.3	16.5, 25.3	16.2 ± 7.6	11.6, 20.7
	6	13.5 ± 4.8	10.6, 16.4	22.3 ± 8.0	17.4, 27.1	18.9 ± 8.1	14.0, 23.8
	7	16.6 ± 7.0	12.4, 20.8	24.3 ± 8.0	19.5, 29.2	19.8 ± 10.0	13.8, 25.9
	8	19.0 ± 9.1	13.5, 24.5	27.4 ± 9.4	21.7, 33.1	22.9 ± 9.5	17.1, 28.6

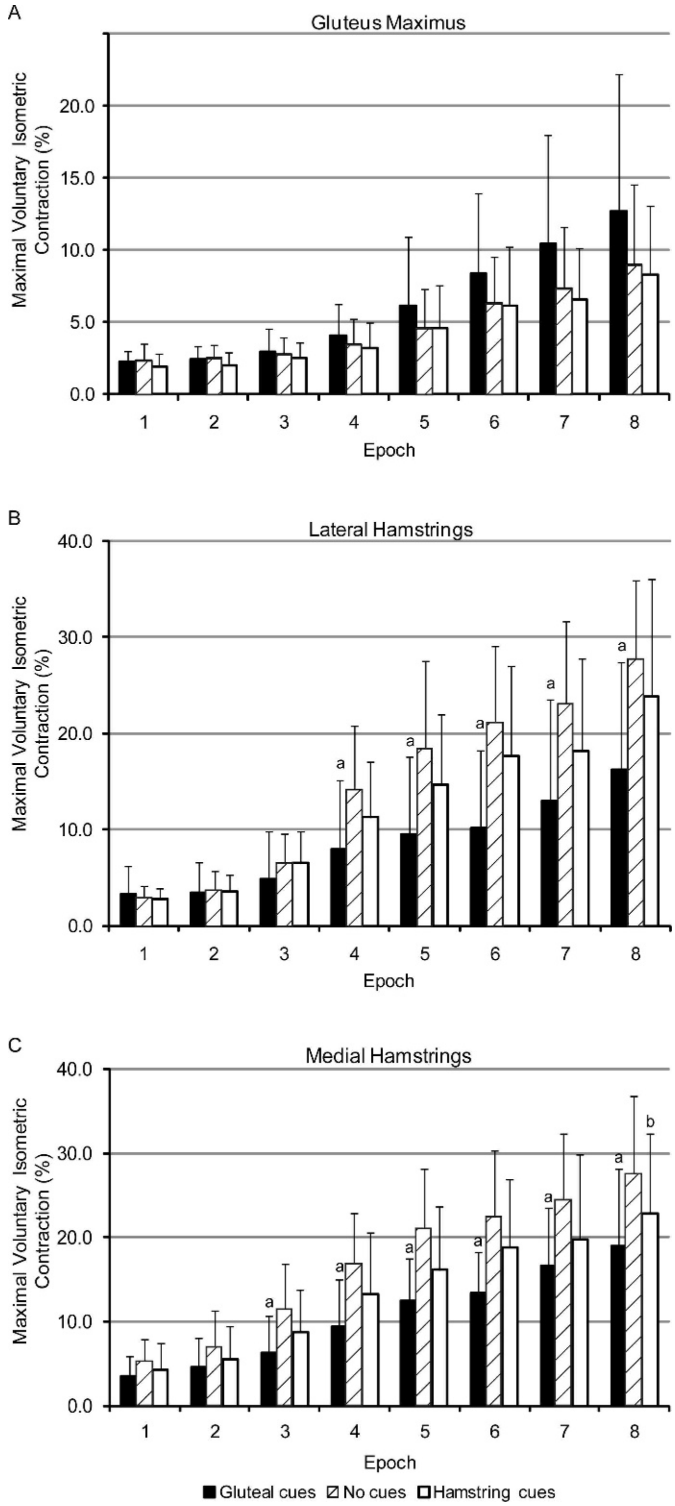

Figure 6. Average amplitude of muscle activation across the 8 epochs surrounding the start of movement, which is the point between epoch 4 and epoch 5, for A, the gluteus maximus muscle; B, the medial hamstrings muscles; and C, the lateral hamstrings muscle. The activation of the medial and lateral hamstrings muscles was lower during the gluteal-cues condition than during the no-cues condition. [a] Indicates $P \leq .03$. The activation of the medial hamstrings muscles was lower in epoch 8 during the hamstrings-cues condition than during the no-cues condition. [b] Indicates $P = .028$.

consistent and distinguishable pattern in the no-cues condition. Despite conflicting information, we and the authors of all these studies agree that hamstrings muscle activity occurs before the onset of movement. We and the authors of 3 of the 4 studies also agree that the activation onset of the gluteus maximus muscle usually occurs after the activation onset of a hamstrings muscle.[8,9,11]

The purpose of the studies mentioned was to examine the activation pattern of multiple muscles attaching to the pelvis and femur during hip extension, but the studies have methodologic differences that may partially account for the inconsistent findings. Although the investigators in each study recorded data from the gluteus maximus muscle and at least 1 of the hamstrings muscles, the total number and specific set of muscles studied was different. Vogt and Banzer[8] recorded data from the most muscles, including bilateral lower rectus abdominus, bilateral erector spinae, ipsilateral semitendinosis, gluteus maximus, rectus femoris, and tensor fascia lata muscles. Pierce and Lee,[10] Lehman et al,[11] and Bullock-Saxton et al[9] recorded data from bilateral erector spinae, ipsilateral gluteus maximus, and lateral hamstrings (biceps femoris) muscles. Our focus was on investigating the relative onset timing of the primary hip extensor muscles, not the pattern of activation of trunk and hip muscles during the motion. Therefore, we evaluated only the EMG data from the ipsilateral medial and lateral hamstrings muscles and from the gluteus maximus muscle, among which we found a consistent order. If we had included more muscles with less consistent timing, we might have had more difficulty finding a pattern of activation.

Another possible reason for disagreement among the studies is the sex of the participants. In a preliminary study that included a limited number of men, we found a main effect of sex on muscle onset times (unpublished data, 2005). Given differences in prevalence of hip dysplasia[29] and acetabular labral tears[15,17,30–32] and differences in hip musculature response to lower extremity or back injury[33] between men and women, it is conceivable that they use different hip muscle activation patterns. Because our larger interest was in women with hip pain, we limited our further analyses to women only. A sex difference in muscle activation could explain why we, Vogt and Banzer,[8] and Bullock-Saxton et al[9] found a consistent pattern in our single-sex studies, but Pierce and Lee[10] and Lehman et al,[11] whose studies included both women and men, did not. Intrinsic sex differences may have obscured detection of a consistent muscle activation pattern.

One procedural difference that may further confuse the order of muscle activation issue is how the exercise was performed. In a preliminary study, we attempted to identify muscle activation onsets in 2 types of trials. In one type of trial, the participant repeatedly lifted and lowered the leg with no rest between trials (repeated trials). In the other type, the participant lifted and lowered the leg, then rested for 2 seconds before lifting and lowering the leg again (rest trials). We found that during the repeated trials, muscle activation onsets were more difficult to identify because EMG activity was continuous between repetitions. Using a paired t test with an α level set at .05, we also found in the repeated trials that the timing of muscle activation onset in the first repetition was different from the timing in any of the subsequent repetitions despite using the same criteria for

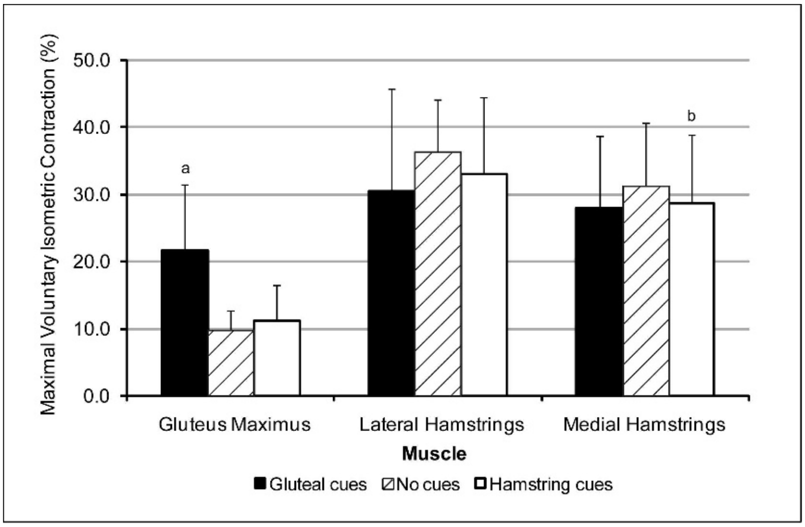

Figure 7. Effect of verbal cues on the average amplitude of muscle activation throughout the hip extension movement. The gluteus maximus muscle activation was higher during the gluteal-cues condition than during the no-cues condition. [a] Indicates $P < .001$. The medial hamstrings muscles activation was lower during the hamstrings-cues condition than during the no-cues condition. [b] Indicates $P = .034$.

determining onset. This difference is most likely due to the level of muscle activity maintained between repetitions in the repeated trials. We did not find this difference among the repetitions in the rest trials because the muscle started from the same point of inactivity with each repetition.

Pierce and Lee[10] used a procedure similar to the repeated trials, whereas Vogt and Banzer[8] and Bullock-Saxton et al[9] allowed participants to rest between repetitions. Lehman et al[11] did not specify which method was used. This difference between repeated and rest trials may also be clinically important when precise timing of muscle activation is desired.

Another difference between the studies is the starting position and stabilization of the participants. In 3 studies, participants started in a neutral hip position and then extended the hip,[8,9,11] whereas participants in our study and the study by Pierce and Lee[10] were initially positioned in 30° of hip flexion. We used this starting position to ensure that our participants had the available range to extend the hip 30° in 1 second and, therefore, to maintain a similar range and velocity of movement for all participants. We were the only researchers to use a stabilization belt across the pelvis. However, these differences do not consistently explain the disagreement among studies regarding the order of muscle activation.

Effect of Cues on Muscle Timing and Amplitude

Clinicians commonly use verbal cues, but we found few reports in the literature about the effect of verbal cues on muscle activation patterns. Verbal cues combined with EMG biofeedback have been used effectively to treat patients with facial nerve disorders.[34] Verbal cues to modify knee joint position have also been effectively used during a landing task, but Cowling et al[35] reported that verbal cues to modify hamstrings muscle activity were ineffective and actually had the opposite of the desired effect.

The instruction to use the gluteal muscles to lift the leg while keeping the hamstrings muscles relaxed is often provided as an intervention in people with hip pain. When instructed to do this in our study, participants were able to activate the gluteus maximus muscle at the same relative time as the hamstrings muscles and delay the activation of the lateral hamstrings muscle. Drawing exact conclusions regarding the absolute timing of muscle activation is difficult because we used a relative reference point based on start of hip extension movement, which may also have been changed. With this verbal cue, we also noted decreased hamstrings muscle activity around the start of movement and increased gluteal muscle activation throughout the movement. This finding supports the use of verbal cues when the goal is increased gluteal muscle activity or decreased hamstrings muscle activity at the initiation of movement. However, the cues to contract the hamstrings muscles while keeping the gluteal muscles relaxed were much less effective. The changes noted were a decrease in medial hamstrings muscle activity 150 to 200 milliseconds after the start of movement (epoch 8), as

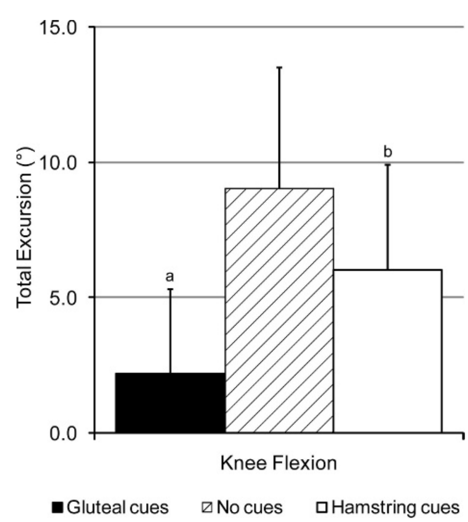

Figure 8. Knee joint excursion throughout the movement. Knee flexion excursion was decreased in both the gluteal-cues and hamstrings-cues conditions compared with the no-cues condition. [a] Indicates $P \leq .01$. [b] Indicates $P = .001$.

well as a slight decrease in the medial hamstrings muscle activity throughout the movement. Similar to results reported by Cowling et al,[35] this finding illustrated that verbal cues for changes in muscle activity do not always have the intended effect.

Effect of Cues on Knee Kinematics

Verbal cues resulted in changes in muscle activity, but these changes may not be easily discernable by palpation or visual inspection. The lateral hamstrings muscle activation onset was just 61.4 milliseconds later during the glut-cues condition than during the no-cues condition. Such small changes would be very difficult to detect by palpation. However, the changes in muscle activation were also accompanied by greater changes in knee flexion excursion of 2.9° and 6.8° throughout the movement for the HS-cues and glut-cues conditions, respectively. These differences in knee flexion occurred despite the tactile cue of tape across the knee. The change in knee flexion excursion may be easier to observe clinically than timing of muscle activation and could be used as an additional tool for monitoring prone hip extension.

Limitations

Using prone hip extension to investigate muscle activation patterns has some limitations. Prone hip extension is not a functional task; therefore, the application of the results of this study to functional tasks, such as walking, remains to be determined. However, evaluation of muscle activation during prone hip extension has been studied because of its similarity to the activation pattern of hip extensor muscles during gait[8,9,11] and its use in clinical examinations.[36] During gait, the hamstrings muscles are activated at the end of swing just before the activation of the gluteus maximus,[37] which is the same order of muscle activation seen in prone hip extension. Furthermore, prone hip extension is often used as a rehabilitation exercise for patients with a variety of conditions.[3,38–41] A more complete understanding of muscle activation during this exercise and functional activities would be beneficial.

Another limitation of prone hip extension is the prescription of a 2-second rest period between repetitions. When analyzing the results of other studies,[8–11,21] we determined that a rest period may be necessary to observe a consistent muscle activation order. During many functional activities, including walking, movement is continuous and, therefore, does not employ a rest period. However, because of the nature of the prone hip extension task, the hip extensor muscles continue to be active during both the hip extension and hip flexion phases of the task. The use of a rest period elicits a phasic muscle activity pattern. This phasic pattern, which has periods of both activity and inactivity, is more consistent with gait than the continuous activity observed in the other task.[42]

Our methods may also be limited because we normalized data using MVIC trials, which were performed after the prone hip extension trials. The MVIC trials are traditionally conducted before the exercise protocol to avoid any effect of fatigue during the testing session. However, because a limited number of prone hip extensions were performed at submaximal effort, it is unlikely that the results of MVIC trials were significantly affected.

CONCLUSIONS

We found that during prone hip extensions, women without hip or back pain displayed a consistent and distinguishable order of muscle activation that began with the medial hamstrings muscles, was followed by the lateral hamstrings muscle, and concluded with the gluteus maximus muscle. Compared with the no-cues condition, the glut-cues condition resulted in nearly simultaneous activation of the gluteus maximus and hamstrings muscles, decreased activation of the hamstrings muscles around the initiation of movement, increased activation of the gluteus maximus throughout the movement, and decreased knee flexion. This information is important for clinicians using prone hip extension as either an evaluation tool or a rehabilitation exercise. Specifically, during clinical evaluation of a patient with hip pain or hip extensor muscle dysfunction, the clinician should monitor the patient for abnormalities in muscle activation order. Furthermore, changes in knee flexion while performing prone hip extension exercises may indicate that the patient is altering muscle activation because of fatigue and needs to rest before continuing the exercise. When making comparisons among patients, the clinician should also take into consideration the sex of the patient, the muscles being monitored, the method of performing prone hip extension, and the motion of the knee. Further study is indicated to determine the effect of sex and whether the order or amplitude of muscle activation or movement is altered in the presence of hip or back pain.

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