Locomotion in restricted space: Kinematic and electromyographic analysis of stoopwalking and crawling☆

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A B S T R A C T

Stoopwalking and crawling are compulsory gait techniques in some occupational settings, as in low-seam coal mines (where vertical space may be less than 122 cm). Nine participants, six males and three females (mean = 35 years + 17 SD), participated in a study examining kinematic and electromyographic (EMG) responses to natural cadence stoopwalking, four-point crawling (all fours), and two-point crawling (knees only). EMG data were collected from knee extensors and flexors, and a motion analysis system was used to obtain kinematic data. The average gait velocity for stoopwalking was 1.01 (±0.32) m/s with an average cadence of 112.8 steps/min and stride length of 1.04 m. Four-point crawling velocity averaged 0.50 (±0.20) m/s, with average cadence of 86.3 steps/min and stride length of 0.69 m. Two-point crawling exhibited the slowest velocity (0.32 m/s) and shortest stride length (0.40 m); however, cadence was greater than four-point crawling (96.8 steps/min). EMG findings included prolonged contraction of both knee extensors and flexors (compared to normative data on normal walking), increased relative activity SD of the flexors (versus extensors) in two-point crawling, and decreased thigh muscle activity in four-point crawling. Interlimb coordination in four-point crawling trials indicated trot-like, no limb pairing, and near pace-like limb contact patterns. Presence or absence of kneepads had no impact on kinematic or EMG measures ($p > 0.05$); however, subjects complained of discomfort without kneepads (especially in two-point crawling). Results of this study have implications for work performed in underground coal mines, as well as emergency or evacuation considerations.

1. Introduction

Successful performance of occupational activities often requires workers to efficiently (and safely) transport themselves from one workplace location to another. This is normally accomplished via upright walking. However, certain occupational environments, such as low-seam coal mines (where vertical height is less than 122 cm), do not permit upright walking. The constrained vertical space compels mine workers to stoopwalk or crawl (either on all fours or on two knees) to fulfill their daily work duties.

Previous studies of stoopwalking and crawling have disclosed higher metabolic demands for gait in vertically constrained space [1–5]. In fact, metabolic costs appear to rise as stooping postures becomes more severe [4,5]. In addition to higher metabolic costs, maximum gait velocity may be reduced as space restrictions become more extreme [4,5]. Crawling speed may also be affected by gender and body composition, with overweight individuals and females exhibiting reduced speed [6]. Crawling speed also impacts interlimb coordination patterns [7].

However, our understanding of locomotion demands in confined space remains incomplete. For example, two-point crawling (crawling on knees alone) had not been investigated, and influence of kneepads on crawling remains unclear. Furthermore, studies have not examined muscle function of the lower limbs in confined space. Accordingly, the following hypotheses were tested in this study: (1) use of stoopwalking and crawling techniques in confined space will impact gait parameters, kinematics, and electromyographic (EMG) activity of knee extensors and flexors, (2) use of kneepads will affect gait and EMG activity, and (3) that the above factors will interact to affect these measures.

2. Methods

2.1. Subjects

Nine subjects (six males, three females) participated in this study. The average age was 35 years ± 17 (mean ± SD), the average

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mass was 69.7 kg ± 10.6 and average stature was 168.0 cm ± 7.6. The mean body mass index (BMI) for these subjects was 24.2 ± 4.0. All subjects operated under terms of informed consent.

2.2. *Experimental design*

Independent variables consisted of kneepad condition (two levels) and locomotion technique (three levels). Kneepad conditions included: (1) not wearing a kneepad and (2) wearing an articulated kneepad (seen in Fig. 1). Locomotion modalities included stoopwalking (bipedal walking with a fully flexed torso), crawling on two knees (two-point crawling), and crawling on hands and knees (four-point crawling) as seen in Fig. 1. Dependent variables included normalized EMG data of knee flexors and extensors and motion analysis data (to determine knee kinematics, interlimb coordination, and gait parameters). EMG activity was collected from left (L) and right (R) pairs of the vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), and semitendinosus (ST). The two kneepad conditions (no kneepad vs. articulated kneepad) were tested in random order. Within each kneepad condition, a restricted randomization determined the order of the three locomotion trials. Based on this randomization scheme, a split–plot analysis of variance (ANOVA) was used to evaluate EMG responses and gait parameters using Dunn–Sidak *post hoc* tests. As an exploratory investigation, Type I error rates were set at a per contrast 0.05 level.

2.3. *Motion analysis*

A motion capture system (Eagle Digital System by Motion Analysis Corporation; Santa Rosa, CA) was used to ascertain body segment kinematics during crawling and stoopwalking tasks. A modified version of the Cleveland Clinic marker set was employed.

2.4. *EMG preparation*

Electrode locations for the thigh muscles were derived from a previous study [8]. Disposable self-adhesive Ag/AgCl dual snap surface electrodes (Noraxon USA Inc.; Scottsdale, AZ) with electrode spacing of 2 cm center-to-center were used. Electrode sites were shaved and cleaned with an EMG skin prep pad (Dynarex Corp.; Orangeburg, NY). Electrodes were placed over the muscle belly, distal to the motor point [8]. Reference electrodes for each of two wireless transmitters were placed at remote sites.

Maximum voluntary contractions (MVCs) were obtained for the thigh muscles of both right and left legs [9], and used to normalize gait EMG [10–14]. The subject was instructed to lie in a supine position in a Biodex® chair with knee and hips at approximately 90° angles. Hips and ankles were secured via Velcro® straps. The subject then performed knee extension or flexion with maximal effort for at least 5 s while verbal encouragement was provided. EMG measurements were made using a Noraxon Telemyo 2400R-worldwide telemetry system with 16 channels (Noraxon USA Inc., Scottsdale, AZ). Several hardware filters were used: first-order high-pass filters set to 10 Hz ± 10% cut-off, and eighth-order Butterworth/Bessels low-pass anti-alias filters set to 500 Hz ± 2% cut-off. The common mode rejection was >100 dB and EMG sampling rate was 1020 Hz.

2.5. *Procedure*

Procedures were approved by the National Institute for Occupational Safety and Health (NIOSH) Human Subject Review Board. After informed consent was obtained, the subject donned a T-shirt, athletic shorts, socks, and shoes appropriate to the needs of the experiment. The motion analysis markers were applied, and

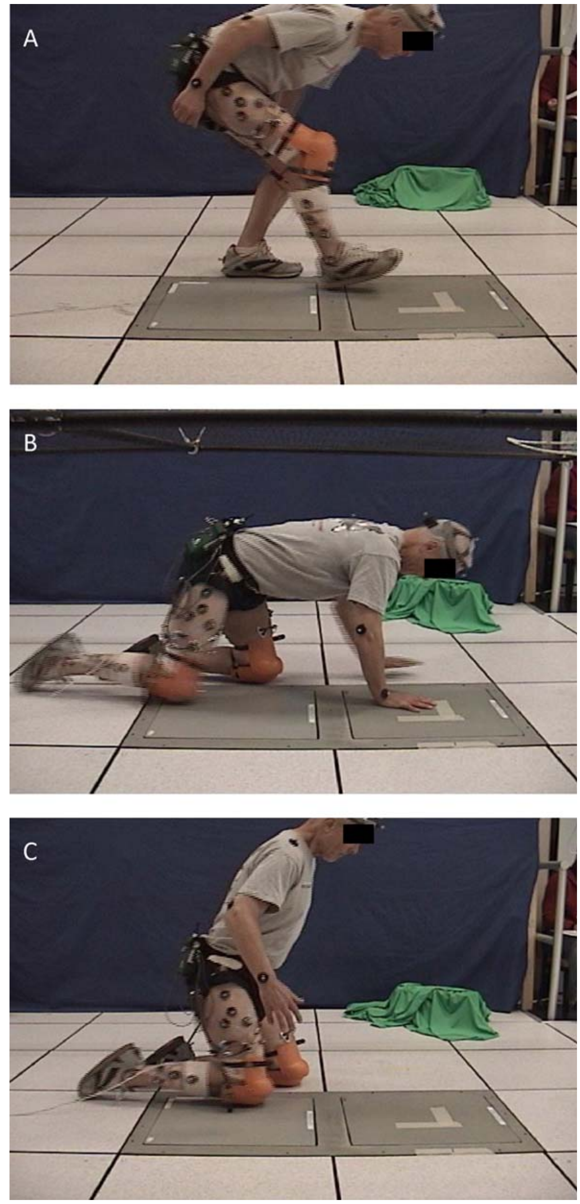

Fig. 1. Subject performing (A) stoopwalk, (B) four-point crawling and (C) two-point crawling with articulated kneepads.

the subject performed motions necessary to develop a body template. EMG electrodes were then applied and MVCs obtained. Depending on the experimental conditions, the subject would don kneepads or remain without kneepads. The subject then performed the three locomotion tasks (in random order) within the specified kneepad condition. Subjects were instructed to stoopwalk or crawl using a natural (free) cadence for each condition [15], and were provided a brief rest period (1–2 min) between trials.

2.6. *Data conditioning and analysis*

Crawling cycles were defined as starting and ending by the position of the left shank marker as the left knee contacted the floor (as determined via motion analysis), while starting and ending times of the stoopwalking cycle were defined by the position of the left ankle marker when the heel contacted the floor. In four-point crawling, the time at which stance and swing phases were initiated for each limb were expressed as a function of the left leg cycle. Interlimb coordination patterns in four-point crawling tasks were assessed by calculating the ipsilateral phase lag (IPL) [7]—the delay between the stance phase of the left arm and stance phase of the left leg. IPLs in the 50% range indicate a *trot-like* gait, where the diagonal limbs enter stance around the same time. IPLs close to 0% or 100% indicate a *pace-like* gait, where ipsilateral limbs contact the ground around the same time. Intermediate values indicate *no pairing of limbs*, with limbs entering stance approximately equally spaced in time.

The EMG signal was rectified and normalized using the MVC for each muscle. Mean amplitude values (MAVs) of the normalized signal were calculated by determining the running mean of every 102 samples, or 10% of the sampling rate [9]. EMG data containing evidence of artifacts were omitted from analysis. Data were analyzed using Statistix software (Analytical Software; Tallahassee, FL).

3. Results

3.1. Temporal and stride measures

Table 1 provides cadence, stride period and length, and gait velocity for stoopwalking and crawling techniques. Gait velocities between methods were significantly different ($F_{2,32} = 96.39$, $p < 0.001$). For stoopwalking, the forward movement speed averaged 1.01 m/s, four-point crawling averaged 0.50 m/s, and two-point crawling averaged 0.32 m/s. *Post hoc* tests indicated significant differences in gait velocities between each of the methods, with a critical value of comparison for the Dunn–Sidak test of 0.12 m/s. Presence or absence of kneepads did not impact speed of locomotion ($F_{1,8} = 3.01$, $p > 0.05$). However, an interaction between locomotion technique and kneepad condition for stride length ($F_{2,32} = 45.17$, $p < 0.001$) and cadence ($F_{2,32} = 11.1$, $p < 0.001$) was observed. Simple effects tests indicated this interaction was due to a decrease in cadence and increased stride length when wearing kneepads in the two-point crawl. Stride parameters in other postures were not affected by wearing kneepads.

3.2. Knee joint kinematics

Fig. 2 presents ensemble averages of included knee angles for the three locomotion methods. The overall angular range of motion of the knee was similar in both stoopwalking and four-point crawling (range of approximately 50–55° in both cases); however, in stoopwalking the included knee angle was more extended (95–150°), while the four-point crawl range involved greater flexion (approximately 55–105°). The range of motion for the knee joint in two-point crawling was limited to about 20°.

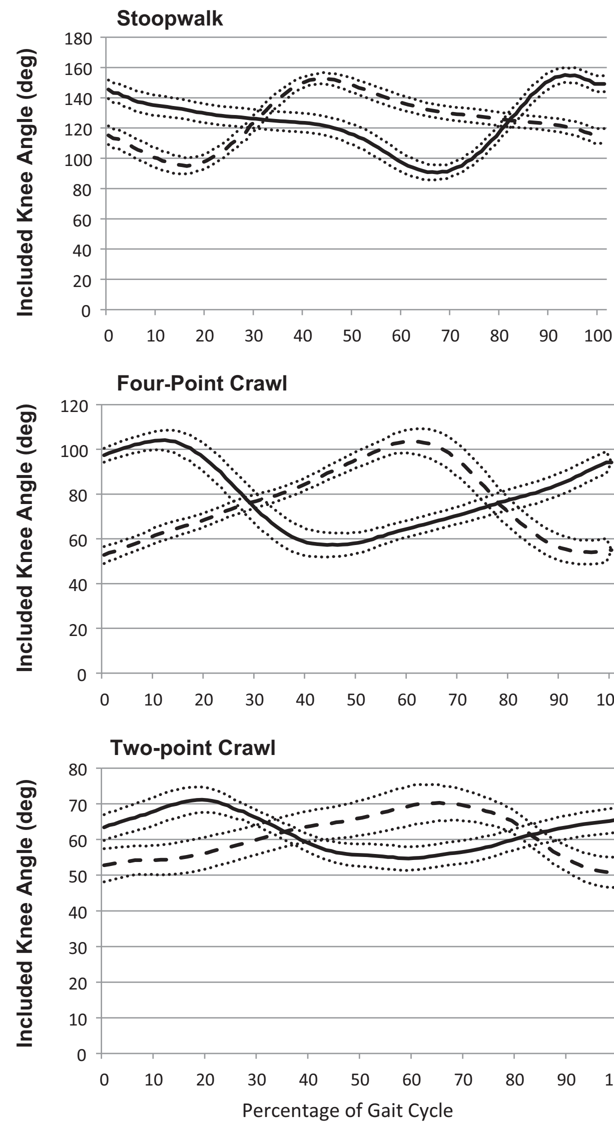

Fig. 2. Ensemble averages for right (solid line) and left (dashed line) knee included angles for stoopwalking, four-point crawling and two-point crawling ($n = 9$).

Table 2 contains data on swing and stance phases during four-point crawling. The arms spent a somewhat larger portion of the cycle in stance compared to the leg (shank). On average, arms were in stance for approximately 70% of the crawling cycle, while shanks were in stance for approximately 55–60% of the cycle.

Table 1
Temporal and stride measures (mean ± SD) for the crawling and stoopwalking methods ($n = 9$).

	Cadence (steps/min)	Stride period (s)	Stride length (m)	Velocity (m/s)
Stoopwalking	112.8 (±40.0)	1.06 (±0.16)	1.04 (±0.24)	1.01 (±0.32)
Four-point crawling	86.3 (±24.6)	1.48 (±0.39)	0.69 (±0.16)	0.50 (±0.20)
Two-point crawling	96.8 (±39.5)	1.24 (±0.19)	0.40 (±0.09)	0.32 (±0.13)

Table 2
Percentages of time in stance and swing for each limb during four-point crawling trials ($n = 9$).

	Lshank		Lwrist		Rshank		Rwrist	
	% Cycle in stance	% Cycle in swing	% Cycle in stance	% Cycle in swing	% Cycle in stance	% Cycle in swing	% Cycle in stance	% Cycle in swing
Mean	56.1	43.9	69.3	30.7	58.0	42.0	69.3	30.7
SD	7.9	7.9	7.5	7.5	7.8	7.8	7.6	7.6

3.3. Interlimb coordination in four-point crawling

Interlimb coordination patterns varied between the subjects, with several distinct IPL groupings observed. Two subjects exhibited IPLs between 41 and 43% (approximating trot-like behavior). Three subjects had IPLs between 35 and 39%, intermediate between trot-like and no-limb pairing patterns. Three subjects demonstrated IPLs between 25 and 29%, indicative of no-limb pairing. One subject exhibited an IPL of 19.6, a value between no-limb pairing and pace-like patterns.

3.4. Electromyography

Fig. 3 provides a summary of average EMG activity for right and left muscle groups for each locomotion method studied. The locomotion mode employed significantly affected the activity of 7 of the 10 muscles studied ($p < 0.05$). Stoopwalking resulted in comparative increases in activity of the LVL, LRF, RVL, RVM, RBF, and RRF muscles according to *post hoc* tests. Two-point crawling resulted in higher activity of hamstring muscles, specifically the RST and LBF ($p < 0.05$). Presence or absence of kneepads did not affect muscle activity ($p > 0.05$). The interaction between locomotion mode and kneepad condition was not significant for any muscle ($p > 0.05$).

4. Discussion

As different positions are adopted for locomotion in confined space, physical demands and loads are redistributed throughout the body. This study specifically examined demands on the lower extremities associated with crawling and stoopwalking activities. Results illustrate differences in EMG activity of the thigh muscles, kinematics of the lower limb, and gait parameters during natural cadence in the three methods studied.

Stoopwalking is clearly the most rapid method of covering ground in restricted vertical space. In fact, stoopwalking was approximately twice as fast as four-point crawling and three times as fast as two-point crawling. The increased gait velocity achieved in stoopwalking is a function of increased stride length and cadence compared to crawling methods. Stride length in crawling activities is handicapped by the decreased lower-limb lever arm afforded in crawling postures (hip-to-knee as opposed to hip-to-foot). Based on anthropometric data presented in Chaffin et al. [16], the effective lever arm for the lower limb would be decreased 54% when hip-to-knee length is compared to hip-to-foot length. However, the reduced lever arm is only one factor in determining stride length – a fact made apparent when comparing the stride length achieved in two-point versus four-point crawling. In four-point crawling, the increased support provided by the hands and arms appeared to free the lower leg for a greater swing resulting in increased stride length.

In comparing existing literature on upright walking to stoopwalking in this study, several previously unidentified differences were documented regarding lower limb kinematics and EMG activity. In kinematic terms, it appears that the range of included knee angles is reduced in stoopwalking when compared to upright walking. The knee joint angles in normal gait reported by Winter [15] range from about a 180° included knee angle (full extension) to approximately 115°. The current study found that full extension of the knee never occurred in stoopwalking. The maximum included knee angle during stoopwalking was only 155°. The lowest included knee angle observed in normal walking by Winter [15] was approximately 115°; whereas, in the present study the knee was flexed almost 90° during stoopwalking. It appears that as vertical space is reduced, joints need to be increasingly flexed to allow the body adequate clearance.

During the weight acceptance phase of normal walking, the knee begins at full extension and there is a slight (20°) knee flexion–extension curve that occurs as weight is transferred from heel to toe [15]. Such a curve was not observed in stoopwalking. In stoopwalking, there is a prolonged flexion phase that subsumes the brief knee flexion–extension phase seen in normal walking. Comparing the data for thigh muscle activity in normal walking [15] to the current study, several differences in EMG activity can be observed. One overall difference is that the thigh muscles are activated for a much longer portion of the cycle in stoopwalking compared to upright walking. The expanded period of muscle activity identified in this study may be one reason for the higher metabolic load observed in stoopwalking compared to upright walking [2–5]. Another notable difference in EMG activity between

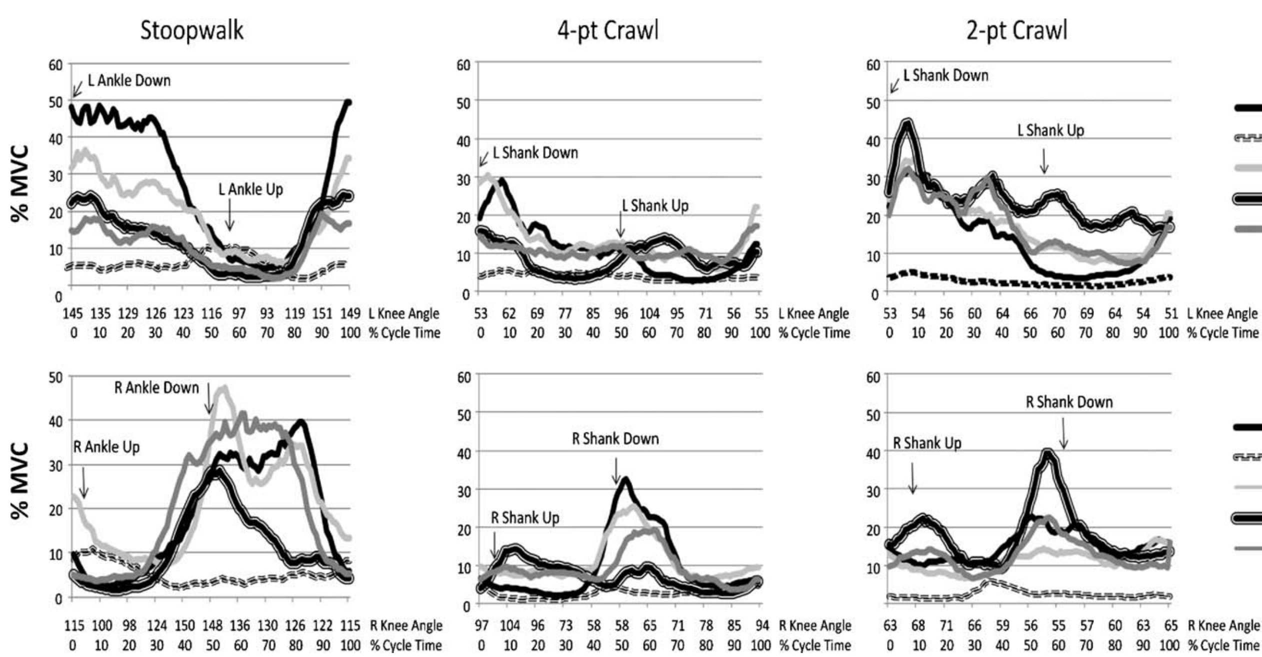

Fig. 3. Left thigh (top row) and right thigh (bottom row) average EMG activity observed in the various locomotion modalities.

walking modalities was observed in the RF. In upright walking, the RF exhibits two periods of activation. The first occurs with extension of the leg prior to heel contact and extension of the knee during the mid-stance phase. However, the current study showed this RF activity is absent in stoopwalking, perhaps due to the lack of full knee extension. A second (minor) burst of RF EMG activity is seen in normal walking just after toe-off and is associated with hip flexion that allows the lower limb to be pulled forward and the knee extension to decelerate the backward swinging of the leg [15]. This RF activity is observed during stoopwalking, as similar actions occur in both walking modes after toe-off.

The knee joint range of motion was decreased in both four-point and two-point crawling when compared to stoopwalking. The total range of knee joint motion for four-point crawling was approximately 50° (Fig. 2). Fig. 2 also shows that approximately 60% of the cycle time was spent in extending the knee (mostly during stance) while the flexion phase was quicker. Fig. 3 illustrates that EMG magnitude for four-point crawling was lower than for stoopwalking. This may be the result of less body weight being supported by the legs in four-point crawling because the arms support the upper body.

Two-point crawling exhibited a restricted range of knee motion (included angles were approximately 50–70°), and differences in muscle activation, compared to the other locomotion modes. Specifically, the hamstrings showed greater activity in two-point crawling, and even exceeded the activity of the vasti muscles, the only posture in which this was observed. It should be noted that the stride length in two-point crawling was only half that observed in four-point crawling, and subjects found two-point crawling to be very uncomfortable. The greater body weight borne by the knees using this technique would appear to exacerbate knee discomfort. This study is the first (to the authors knowledge) to quantify gait measures and thigh EMG activity in two-point crawling.

The velocity of four-point crawling observed in the current study (0.50 m/s) is generally similar to velocities observed in previous studies [7,17,18]; however, these velocities are somewhat slower than those observed in studies in which crawling was examined in a building escape context [6,19]. One study reported a maximum crawling speed of 0.64 m/s [17]; in another study, subjects averaged 0.38, 0.59, and 0.82 m/s for slow, medium, and fast crawling gaits [18]; and a third study examined a wide-range of crawling velocities from 0.22 to 1.34 m/s [7]. The crawling speeds for the escape context studies reported a normal crawling speed of 0.71 m/s and maximum crawling speed of 1.47 m/s [6,19]. It should be noted that such velocities may not be possible in mines given the rough/wet ground conditions usually present. The stoopwalking velocity observed in the current study (1.01 m/s) can be compared to another study where the natural cadence upright walking velocity was 1.33 m/s, representing a 26% decrease for stoopwalking [15]. Although the cadence of 112.8 strides/min for stoopwalking is similar to the 105.3 strides/min observed in the previous study for natural walking [15], the stride length observed for stoopwalking in this study was 1.04 m, considerably less than the 1.51 m for natural walking [15]. Thus, the reduced stride length in stoopwalking is not fully compensated for by the modest increase in cadence, resulting in a reduction in speed.

Several limitations must be noted with the current study. Firstly, it must be acknowledged that the sample size was rather limited. Furthermore, the circumstances of the present study did not allow testing of actual low-seam underground miners. It would be expected that workers who must function everyday in the mining environment would adapt and develop greater efficiency in their movement patterns in restricted postures. Therefore, the results of the current study should be understood to represent the gait responses of relative novices to this environment. Even so, it must be recognized that many of the gait influences demonstrated in this paper are intrinsic to the environment, and while individuals may become more efficient at gait, many of the influences demonstrated in this study would be present no matter the individual skill level. In addition, the current subjects over represent the proportion of females typically found in mining. Finally, results of this study provide gait data over a fairly short distance, so the data would not reflect influences such as fatigue on gait patterns. Nonetheless, results of this study would seem to have important implications for activities such as escape or taking refuge in underground mines. The distance covered in escape situations is important for mine evacuation/escape situations, and the locomotion technique employed will clearly impact the time needed to cover a given distance in such circumstances.

5. Conclusions

The following conclusions are drawn from the current study:

1. The highest gait velocity in confined space is achieved with stoopwalking, followed by four-point and two-point crawling.
2. Wearing kneepads did not influence thigh muscle EMG or knee kinematics during stoopwalking or crawling; however, wearing kneepads in two-point crawling decreased cadence and increased stride length.
3. Compared to upright walking, EMG activity of the thigh muscles during stance in stoopwalking is more prolonged.
4. A variety of interlimb coordination patterns were observed in four-point crawling, including trot-like, pace-like, and no-limb pairing contact patterns.
5. Two-point crawling was unique among the techniques in that the hamstrings exhibited greater activity than the vasti muscles.

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