Characteristics of Gait in Restricted Vertical Space Versus Unrestricted Walking

Sean Gallagher, Ph.D.
Jonisha Pollard, M.S.
William L. Porter, M.S.
National Institute for Occupational Safety and Health, Pittsburgh, Penna.

Upright walking is not a viable gait option in work environments that have restricted vertical space, such as underground low-seam coal mines (< 1.2 m vertical height). In such circumstances, stoopwalking and crawling must be used. The objective of the current manuscript is to assess the difference between free cadence walking versus stoopwalking (under a 1.2 m ceiling), four-point crawling (hands and knees), and two-point crawling (knees only), both with and without kneepads. Compared to upright walking, stoopwalking resulted in a 24% reduction in gait velocity and exhibited reduced stride length (1.04 versus 1.51 meters). Four-point crawling further slowed gait (to 0.50 m/s) and showed evidence of both trot-like and pace-like interlimb coordination patterns. Gait speed for two-point crawling was only 0.32 m/s.

Introduction

Workers are often required to move around from place to place at their worksite in order to perform their daily tasks. In most work environments, this can be easily accomplished via normal upright walking. However, there are occupational environments where upright walking is not possible. One such environment is a low-seam coal mine (defined as a mine with less than 1.2 m vertical height). The restricted space compels mine workers to stoopwalk (bipedal walking while severely bent at the waist with increased knee flexion) or crawl (either on all fours or on two knees) to fulfill their daily work duties.

Early research efforts on restricted space work environments indicated that restricted space locomotion was associated with higher metabolic costs [Moss 1934, Bedford and Warner 1955, Humphreys et al. 1962, Morrissey et al. 1985]. In addition, studies have found that the maximum speed attainable is decreased in severe stoopwalking (< 70% stature) and crawling activities [Morrissey et al. 1985]. However, to date no studies have compared stoopwalking, and crawling to existing data on natural cadence upright walking, either in terms of gait velocity or in comparing knee extensor and flexor electromyographic (EMG) activity to knee kinematics. The current manuscript will assess the differences between natural cadence upright walking versus stoopwalking (under a 1.2 m simulated mine roof), four-point crawling (hands and knees), and two-point crawling (knees only), both with and without kneepads.

 DOI 10.1518/107118110X12829369834087

Method

Subjects

Nine subjects (six males, three females) participated in this study. The average age was 35 ± 17 (mean ± SD) years, while the average mass was 69.7 kg ± 10.6 and the average stature was 168.0 cm ± 7.6. The average body mass index (BMI) for these subjects was 24.2 ± 4.0. Prior to participating in the study, each subject read and signed an informed consent form approved by the National Institute for Occupational Safety and Health (NIOSH) Human Subjects Review Board. One subject had been previously diagnosed with bursitis, which did not require any intervention, and a second subject had slight nerve damage due to a motorcycle accident. However, neither subject was symptomatic at the time of testing, and both were approved for testing.

Restricted Space Locomotion Data

Independent variables in this study were kneepad condition (two levels) and locomotion style (three levels). Kneepad conditions included: (1) no kneepad, and (2) wearing an articulated kneepad with a hard contoured outer shell. Locomotion modes included stoopwalking (bipedal walking with a fully flexed torso in a 122 cm vertical space), crawling on two knees (two-point crawling) in a 122 cm vertical space, and crawling on hands and knees (four-point crawling) in a 97 cm vertical space. Dependent variables consisted of the mean and maximum normalized EMG data of 10 thigh muscles (to ascertain muscle function) and motion analysis data (used to measure knee kinematics and to calculate gait velocity for each locomotion mode/kneepad combination). EMG activity was collected from left and right pairs of muscles including the vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), and semitendinosus (ST).

Motion Analysis

A motion capture system, the Eagle Digital System from Motion Analysis Corporation, Santa Rosa, Calif., was used to determine the location of body segments as the subject performed the crawling and stoopwalking tasks. A modified version of the Cleveland Clinic marker set was used. Reflective markers could not be placed on medial and lateral aspects of the knee when wearing kneepads. Therefore, a full marker set was first developed that included these knee markers followed by a second marker set, where the knee markers were removed from the subject. The second marker set was then used during testing.

EMG Preparation

Preferred locations of the electrodes for each of the thigh muscles were derived from Ericson et al. [1985]. Disposable self-adhesive Ag/AgCl dual snap surface electrodes (Noraxon USA Inc.; Scottsdale, Ariz.) with electrode spacing of 2 cm center-to-center were employed. Each electrode site was shaved (if necessary) and cleaned using a skin prep pad consisting of 70% isopropyl alcohol and pumice (Dynarex Corp.; Orangeburg, N.Y.). Electrodes were placed over the belly of the muscles, distal to the motor point regions [Ericson et al. 1985]. Two reference electrodes were required (one for each wireless transmitter) and were placed at remote sites.

Maximum voluntary contractions (MVCs) were obtained for the thigh muscles of both right and left legs [NIOSH 1992], and they were used to normalize the gait EMG [Dubo et al. 1976; Ericson et al. 1986; Knudson and Johnston 1993]. The subject was instructed to lie in a supine position in a Biodex chair with the included knee angle at approximately 90 degrees with the hips and ankle secured via Velcro straps. The subject was then instructed to perform knee extension with maximal effort for at least 5 seconds while a researcher provided verbal encouragement. The subject was then instructed to flex the knee for that leg with maximal effort for at least 5 seconds again with verbal encouragement. All EMG measurements were made using a Noraxon TeleMyo 2400R—worldwide telemetry system with 16 channels (Noraxon USA Inc.; Scottsdale, Ariz.). The gain was set to 10 for all channels. Several hardware filters were in place: 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 > 100dB. The sampling rate for all EMG data was 1020 Hz.

Procedure

After informed consent was obtained from the subject, the subject donned a T-shirt, athletic shorts, socks, and shoes; then the initial marker set was applied. Subsequently, the subject stood upright and assumed a standing "T-pose" (with arms outstretched to the right and left and parallel with the floor) in order to calculate the positions of the markers that were removed during testing. Selected markers were then removed, EMG electrodes were positioned on the subject, and MVCs were obtained.

Depending on the experimental conditions, the subject was instructed to either don the kneepads or participate without kneepads. The subject then performed all three of the locomotion tasks (in random order) within the specified kneepad condition. Subjects were instructed to stoopwalk or crawl using a natural (free) cadence for each kneepad condition [Winter 1991] and were provided a brief rest (1–2 minutes) between trials. When the trials were completed for a kneepad condition, the subject adopted the opposite kneepad condition and performed all locomotion trials, in random order.

Data Conditioning and Analysis

Locomotion cycles were defined for crawling and stoopwalking trials as follows: crawling cycles were defined as starting and ending by the position of markers on the left shank as the left knee contacted the floor (as determined via motion analysis); stoopwalking cycle starting and ending times were defined by the position of the left ankle marker when the heel contacted the ground. At least two complete cycles of data were collected for all crawling trials; however, for some subjects with long strides only one full cycle of motion analysis data was available for stoopwalking trials. For this reason, the data reported in the results represents one cycle per subject for stoopwalking and the average of two cycles per subject for crawling tests.

Electromyography data was low-pass filtered to 500 Hz and high-pass filtered to 20 Hz using a fourth-order Butterworth filter (MATLAB®; The MathWorks, Inc.; Natick, Mass.) The signal was then rectified and normalized by dividing by the maximum voluntary contraction for each muscle. Mean absolute values (MAVs) of the normalized EMG were then calculated by determining the running mean of every 102 samples, or 10% of the sampling rate [NIOSH 1992]. Trials containing evidence of artifacts were eliminated from the analysis. Ensemble averages for EMG data were generated by normalizing the muscle activity for all subjects in terms of the percentage of the gait cycle.

Comparison Data for Upright Walking

Comparison data for natural cadence upright walking was obtained from Winter [1991]. This reference provides normative data on joint angle histories, EMG activity, and gait velocity during walking.

Results

Temporal and Stride Measures

Table 1 provides average values for cadence, stride period and length, and gait velocity for upright walking, stoopwalking, and crawling. Presence or absence of kneepads did not have any impact on speed of locomotion ($F_{1,8} = 3.01, p > 0.05$).

Knee Joint Kinematics

Figure 1 illustrates joint angle histories for the knee joints for natural cadence upright walking, stoopwalking under a 122 cm ceiling, four-point crawling under a 97 cm ceiling, and two-point crawling under a 122 cm ceiling. It can be seen from this figure that the overall range of angles was similar between walking and stoopwalking (approximately 65 degrees); however, stoopwalking resulted in included knee angles that were generally 25 degrees less (i.e., more flexed) than normal walking. The range of motion of the knee joint was observed to be decreased in four-point crawling and especially in two-point crawling compared to stoopwalking. The total range of motion for the four-point crawling was approximately 50 degrees (55 to 105), while a very limited range of knee joint angles was observed in two-point crawling (50 to 70 degrees included knee angle).

Electromyography

Figure 2 provides ensemble averages for the EMG data provided by Winter [1991] for upright walking and from the current study for stoopwalking and crawling. EMG normalization procedures varied between Winter [1991] and the current study, thus direct comparisons of EMG magnitude are not possible. In addition, the Winter [1991] EMG data appears to be heavily smoothed.

Discussion

As postures change for the purpose of locomotion in restricted space, so do the physical demands on specific regions of the body. This study specifically examined the demands on the lower extremities associated with crawling and stoopwalking activities and compared EMG and kinematic results to those observed in natural cadence upright walking. Figure 2 provides comparisons between gait conditions in terms of EMG activity. For example, in stoopwalking there appears to be a more prolonged period of vastus medialis and vastus lateralis activation. Another notable difference is that the major burst from the rectus femoris during normal walking (associated with the full knee extension in mid-stance) is totally absent in stoopwalking. This may be because the knee never fully extends in mid-stance during stoopwalking (per the kinematic data discussed above). Further, it can be seen that the knee extensor/flexor activation is generally lower in four-point crawling compared to other locomotion techniques. This is likely the result of a decreased burden on the legs to provide forces necessary for locomotion (owing to the assistance of the arms in this type of movement).

In this study, comparisons between existing literature on unrestricted walking and stoopwalking disclosed several differences in terms of both kinematics and EMG activity of the thigh muscles. In kinematic terms, it appears that the range of included knee angles are somewhat reduced in stoopwalking compared to upright walking. The range of the included knee angles reported by Winter [1991] in normal gait went from about 180 degrees (full extension) to approximately 115 degrees. The current study found that full extension of the knee never occurred in stoopwalking. In fact, the maximum included knee angle during stoopwalking was approximately 155 degrees as opposed to the 180 degrees observed in normal walking. The lowest included knee angle observed in normal walking by Winter [1991] was approximately 115 degrees, while the knee was flexed almost 90 degrees during stoopwalking. Thus, stoopwalking resulted in included knee angles that were generally 25 degrees less than during normal walking. The reduced included knee angles would appear to be a consequence of the space restrictions present. As space becomes more confined, joints (such as the knee joint) need to maintain a flexed position so that the body can maintain adequate clearance in the reduced vertical space.

The total knee joint range of motion for four-point crawling was approximately 50 degrees (55 to 105 included angle). Examining the pattern of motion (Figure 1) indicates that approximately 60% of the cycle time was spent in extending the knee (mostly during the contact phase) while the flexion phase (as the leg was brought forward) occurred more quickly. The magnitude of EMG for four-point crawling was lower in general (and periods of significant activity less prolonged) than for standing or stoopwalking. This may be due in part to less body weight being supported in four-point crawling due to the support of the upper body by the muscles of the arms and shoulders (which could not be quantified in the current investigation). As with stoopwalking, higher activity was observed for the VL and VM with lesser coactivity of the medial and lateral hamstrings. Activity of the RF was minimal in both crawling postures.

References

Bedford T, Warner CG [1955]. The energy expended while walking in stooping postures. Br J Ind Med *12*(4):290–295.

Dubo HI, Peat M, Winter DA, Quanbury AO, Hobson DA, Steinke T, Reimer G [1976]. Electromyographic temporal analysis of gait: Normal human locomotion. Arch Phys Med Rehabil *57*:415–420.

Ericson MO, Nisell R, Arborelius UP, Ekholm J [1985]. Muscular activity during ergometer cycling. Scand J Rehabil Med *17*(2):53–61.

Ericson MO, Nisell R, Arborelius UP, Ekholm J [1986]. Quantified electromyography of lower-limb muscles during level walking. Scand J Rehabil Med *18*:159–163.

Humphreys PW, Lind AR, Sweetland KS [1962]. The energy expenditure of coal-miners at work. Br J Ind Med *19*:264–275.

Knudson DV, Johnston D [1993]. Comparison of EMG normalization methods in a sit-to-stand movement. J Hum Mov Stud *25*:39–50.
Morrissey SJ, George CE, Ayoub MM [1985]. Metabolic costs of stoopwalking and crawling. Appl Ergon *16*(2):99–102.

Moss KN [1934]. The energy output of coal miners during work. Trans Inst Min Eng *189*:132–149.

NIOSH [1992]. Output forms: data analysis and applications. Chapter 5 in Selected topics in surface electromyography for use in the occupational setting: Expert perspectives. By LeVeau B, Andersson GBJ. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 91-100.

Winter DA [1991]. The biomechanics and motor control of human gait: normal, elderly and pathological. 2nd ed. Waterloo, Ontario (Canada): Waterloo Biomechanics, 59-61.

Table 1. Average values for temporal and stride measures for upright walking [Winter 1991], stooping, and crawling.

	Cadence (steps/min)	Stride Period (s)	Stride Length (m)	Velocity (m/s)
Upright walking (n=53)	105.3	1.14	1.51	1.33
Stoopwalking (n=9)	112.8	1.06	1.04	1.01
Four-point Crawling (n=9)	86.3	1.48	0.69	0.50
Two-point Crawling (n=9)	96.8	1.24	0.40	0.32

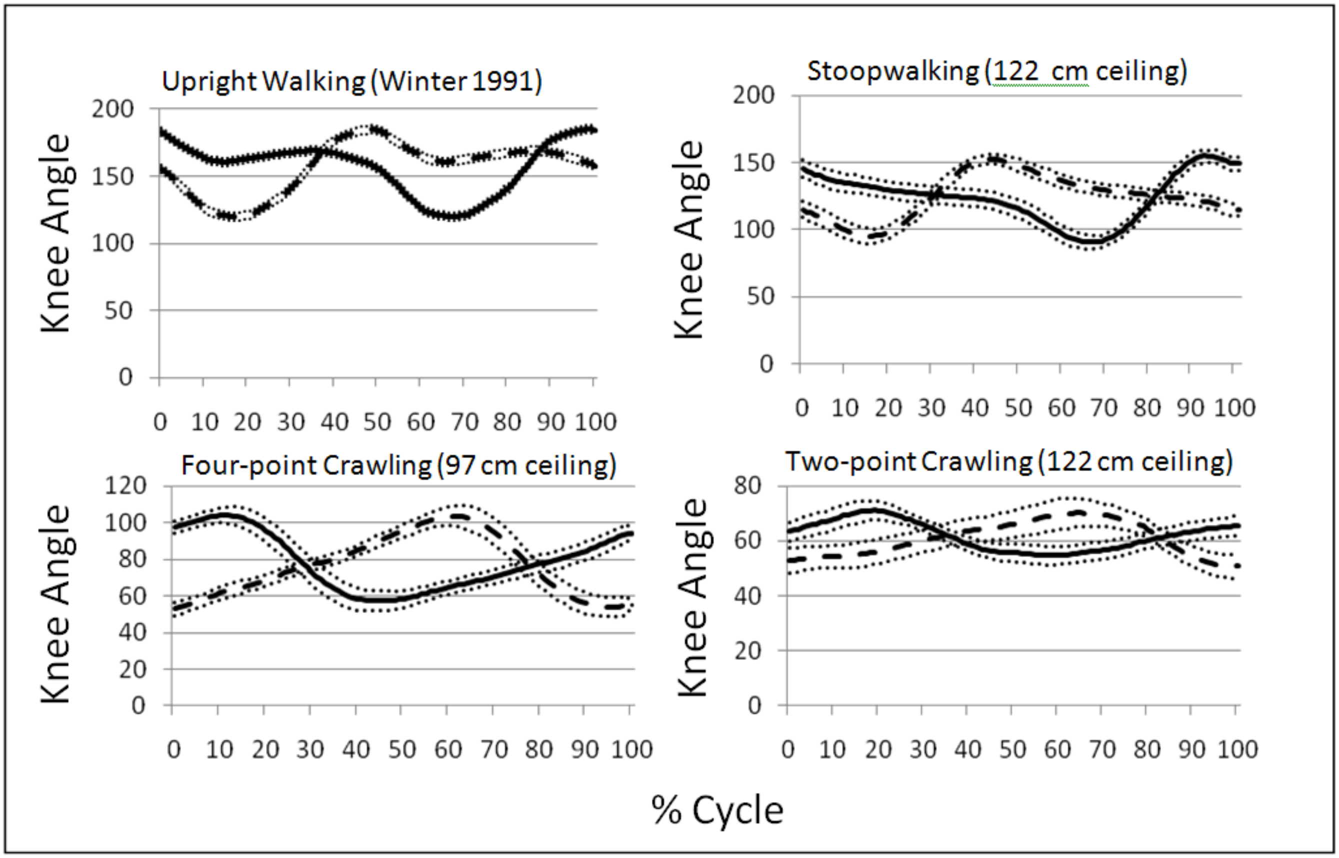

Figure 1. Included knee angles (dotted line = ± SE) for walking (Winter 1991), stoopwalking, four-point crawling and two-point crawling. Solid lines represent left knee angles and dashed lines represent right knee angles.

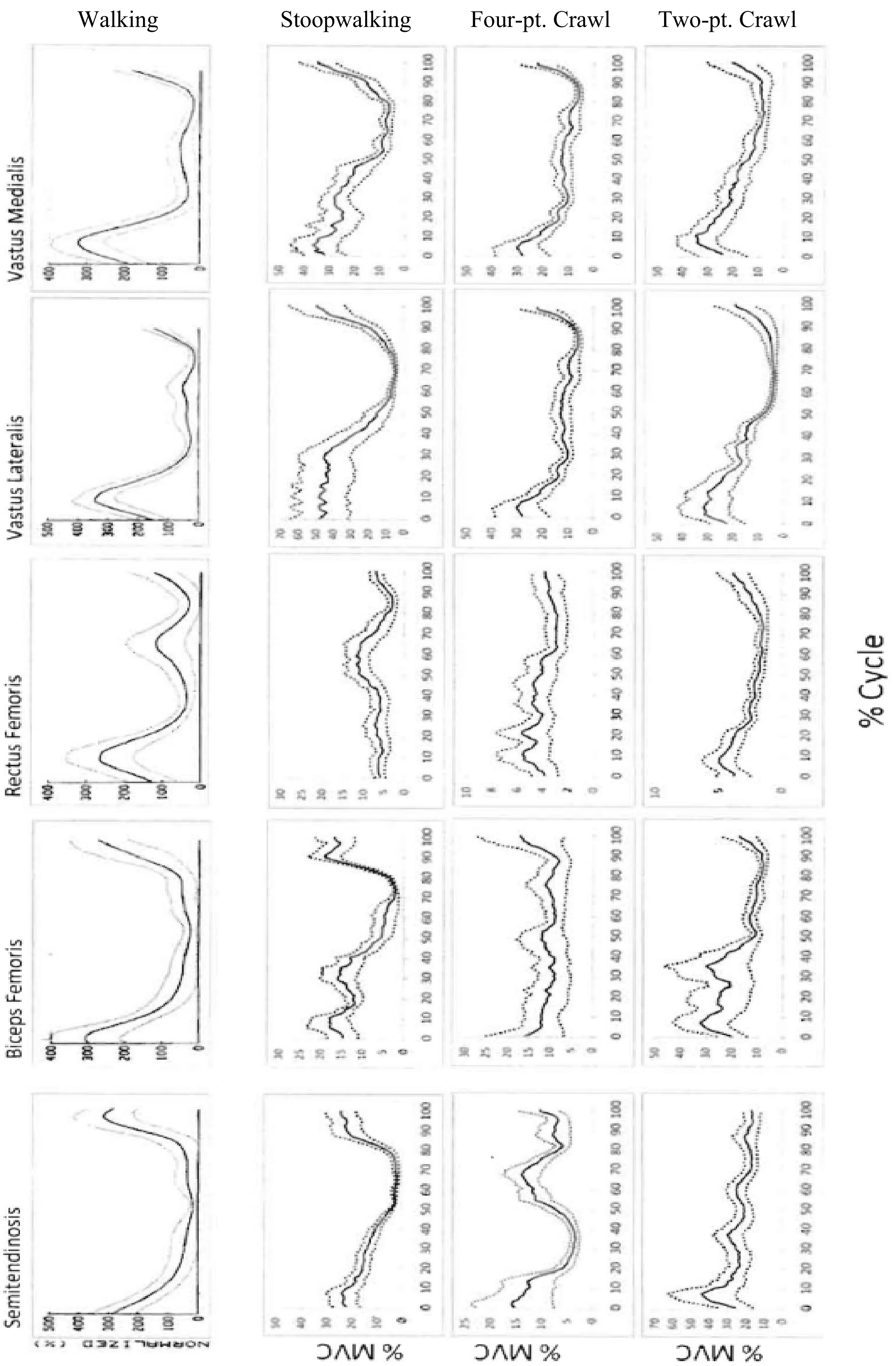

Figure 2. Thigh muscle EMG ensemble averages for upright walking [Winter 1991] in the top row versus stoopwalking (second row), four-point crawling (third row), and two-point crawling (fourth row). Note that normalization procedures by Winter (1991) differ from the current study. MVC = maximum voluntary contraction. Dotted lines represent ± SE.