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

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ABSTRACT

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 ($\pm$0.32) m/s with an average cadence of 112.8 steps/min and stride length of 1.04 m. Four-point crawling velocity averaged 0.50 ($\pm$0.20) m/s, with average cadence of 86.3 steps/min and stride length of 0.69 m. Two-point crawling exhibited the slowest velocity (0.32 m/s) and shortest stride length (0.40 m); however, cadence was greater than four-point crawling (96.8 steps/min). EMG findings included prolonged contraction of both knee extensors and flexors (compared to normative data on normal walking), increased relative activity SD of the flexors (versus extensors) in two-point crawling, and decreased thigh muscle activity in four-point crawling. Interlimb coordination in four-point crawling trials indicated trot-like, no limb pairing, and near pace-like limb contact patterns. Presence or absence of kneepads had no impact on kinematic or EMG measures ($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.

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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 $\pm$ 17 (mean $\pm$ 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

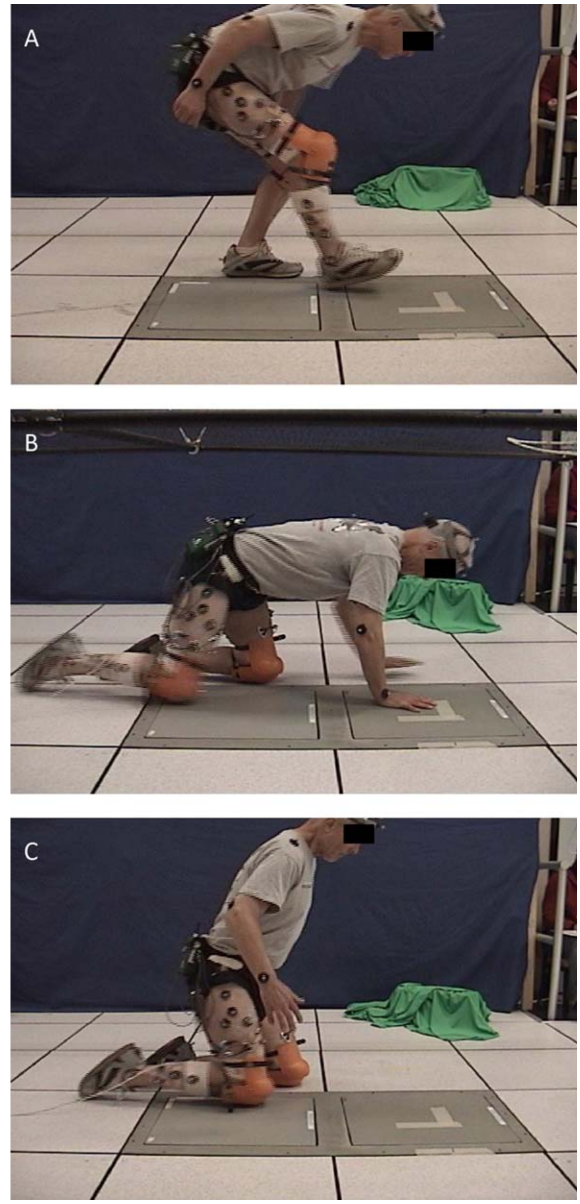

Fig. 1. Subject performing (A) stoopwalk, (B) four-point crawling and (C) two-point crawling with articulated kneepads.

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