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Partial rupture of the Achilles tendon during a simulated fire ground task: Insights obtained from a case report for the prevention and reporting of musculoskeletal injury

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ABSTRACT

Background: In this case report an incumbent firefighter partially ruptured his right Achilles tendon during a study of the physical demands of firefighting.

Methods: Kinematics and kinetics of the lower limbs and trunk were collected while the firefighter performed two simulated fire ground tasks. From this unexpected event, two insights were obtained that should be considered in all future injury prevention and reporting efforts.

Findings: (i) Consider the full anatomical linkage — the right ankle and knee kinematics leading up to the onset of injury trial were comparable to all preceding repetitions. However, there was a notable difference in the left knee starting position before the initiation of movement of the 37th hose-advance trial. (ii) Consider the cumulative load — the task in question comprised forward and backward phases. A marked difference was observed in the frontal-plane ankle moment during the return phase of the trial preceding the injury. Additionally, the magnitude of the left side vertical ground reaction force was comparable across all trials, suggesting that loads experienced by the right limb were also similar. This would indicate that the tolerance of the Achilles tendon and not the magnitude of the loading was altered.

Interpretation: The unfortunate injury captured in this work provides insight into the complexity of characterizing the pathways of injury. It is recommended that future injury prevention and reporting efforts consider individuals' physical demands (at work and in life) and document the nature of loading (i.e., frequency, duration, magnitude, type) when considering the mechanism for injury.

1. Introduction

The underlying mechanical theory for musculoskeletal injury suggests that tissue damage occurs when the physical demands exceed the tissue's capacity. There are two primary pathways in which tissues can be overloaded. The first mechanism, often described as an acute or overexertion injury, occurs when a single load exposure exceeds a tissue's failure tolerance. A second way that tissues can be damaged is through repeated (or sustained) application of loads that are of sub-failure magnitude. This cumulative injury mechanism, often attributed to overuse, reduces a tissue's capacity, which over time will result in failure when the accumulation of damage outpaces the rate of recovery (Kumar, 1990; McGill, 1997). Although straightforward in principle, differentiating between overexertion and overuse injury mechanisms can be quite difficult in practice.

Acute injury pathways can be used to describe the mechanisms of tissue failure that occur during traumatic workplace accidents (e.g., slips, trips and falls). In such cases, the mechanical loading that is applied to the human body often exceeds safe exposure levels, which results in injury. However, discretion must be exercised when a musculoskeletal injury is attributed to a specific occupational task, unless the tissue's short- and long-term loading history is known (McGill, 1997). It is important to consider an individual's physical demands, both at work and in life because many musculoskeletal injuries are the result of cumulative damage to a tissue, even though they are often attributed to a single culminating event. Current surveillance and injury reporting is linked to statistics obtained from reports that require workers or health and safety personnel to identify a single event as the cause.

In a recent study conducted by our group, we observed an incumbent firefighter partially rupture his right Achilles tendon (AT) during an experiment conducted to provide insight into the physical demands of firefighting. Upon reviewing the biomechanics data that were collected, it is the authors' contention that the initiation of severe tissue damage occurred during the backward phase of the preceding trial; however, the injury was likely the result of cumulative damage to the tendon. Therefore, the purpose of this case report is to document the injury process, using the biomechanical data that

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were collected, and provide insight into cumulative injury pathways associated with occupational physical exposures.

2. Methods

2.1. Participant

Biomechanical data collected from a 32 year-old male firefighter (height = 172 cm; mass = 80 kg) are presented in this case report. The inclusion criteria for the investigation specified that all participants were free of musculoskeletal injury and pain and on full-active duty at the time of collection. Ethics approval for this study was obtained from the University Human Ethics Research Committee.

2.2. Simulated fire ground tasks

Given the established link between cumulative trauma injury and cumulative load, it is important to acknowledge that the experiment comprised two tasks commonly performed by incumbents on the fire ground, which were simulated in a biomechanics laboratory. These included: (i) a hose-advance; participants were instructed to place a 6.4 cm diameter rope (connected to a weighted cable machine; 10 kg resistance) over the right shoulder and initiate forward motion from a stationary, staggered stance (left foot forwards). Participants initiated forward motion with the right foot and were asked to complete 2 to 3 strides in the forwards direction (Fig. 1A); and (ii) a forced entry; participants struck a ceiling-mounted “heavy bag” with a 4.5 kg sledgehammer to simulate a forced entry into a building (Fig. 1B). However, since the evidence for the mechanism of injury was contained in the hose-advance task, only the data from trials prior or during this task are reported here.

2.3. Instrumentation

Clusters of 5 or 6 Optotrak® Smart Markers (Northern Digital Inc., Waterloo, ON, Canada) affixed to segment-specific plastic rigid bodies were secured to the feet, shanks, thighs, pelvis and thorax (8 rigid bodies in total) using double-sided tape and Velcro® straps. Marker position data were sampled at 32 Hz using four Optotrak Certus® position sensors (Northern Digital Inc., Waterloo, ON, Canada). Ground reaction forces and moments from each lower limb were recorded synchronously at 2048 Hz from two in-ground force platforms (AMTI, Watertown, MA, USA) using a 16-bit analog to digital conversion board (Optotrak® Data Acquisition Unit II, Northern Digital Inc., Waterloo, ON, Canada). After calibrating the motion capture collection volume and aligning the coordinate system of each position sensor to a common laboratory system, the location of each force platform was located by digitizing each of their four corners using a digitizing probe (Northern Digital Inc., Waterloo, ON, Canada).

2.4. Protocol

The participant donned a t-shirt, shorts and his own athletic shoes for data collection. Upon arriving to the lab, the participant was instrumented with the eight rigid bodies used for motion capture. Next, the locations of the proximal and distal endpoints of each segment (i.e., feet, shanks, thighs, pelvis and trunk; 23 anatomical landmarks) were identified using a digitizing probe. A static (standing) calibration trial was collected such that the orientation of each segments' local coordinate system, as defined by the anatomical landmarks and segment endpoints, could be determined using a transformation from the coordinate system established for each rigid body. Functional hip joint centers (HJC) and knee joint axes (KJA) were determined using similar methods to those described by Begon et al. (2007) and Schwartz and Rozumalski (2005). Briefly, the participant was asked to perform 10 repetitions of open-chain knee flexion/extension and hip flexion/extension, ab/adduction and circumduction. From these motion data, Visual 3D™ software (Version 4.96.6, C-Motion, Inc., Germantown, MD, USA) was used to compute the axis of rotation between each pair of measured segment orientations. The most likely intersection and orientation of the axes were used to define the effective HJCs and KJAs, respectively.

Following these trials, the participant was familiarized with the simulated fire ground tasks using a standard set of instructions. The demands of these tasks were based on the Candidate Physical Ability Test (CPAT), which reflects the critical tasks and essential duties of firefighters. Participants were encouraged to perform the task as they would on the job. Twenty-five repetitions of each movement were collected in a block-randomized order (i.e., in sets of five consecutive repetitions). Approximately 15 s and 2 min of rest were provided between trials and tasks respectively. Once five sets of each task were completed (S1), the participant was provided with 15 min of rest, before starting a second collection (S2) comprising another 25 repetitions of each task. However, partway through the second test session, during the 37th of 50 trials of the hose-advance task, the

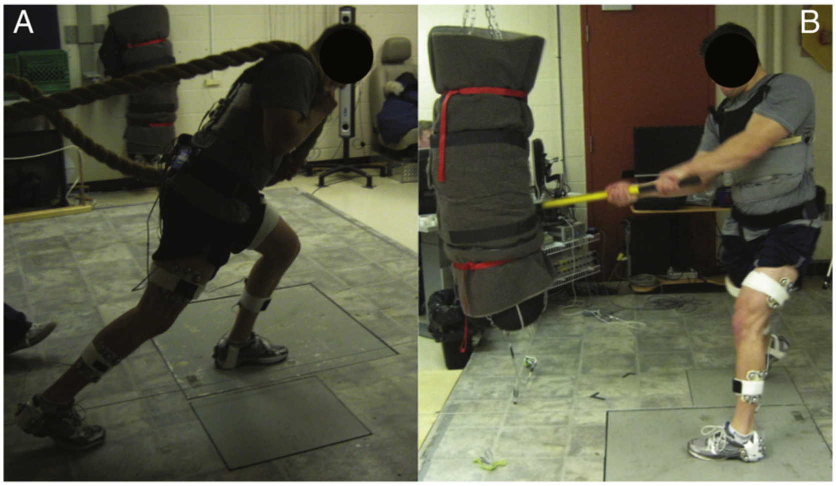

Fig. 1. (A) Simulated hose-advance task with a 6.4 cm diameter rope connected inline to a weighted cable machine with 10 kg resistance. All trials commenced with the participant's left foot on the force platform (B) Simulated forced entry task with a 4.5 kg sledgehammer.

incumbent firefighter partially ruptured his right AT. Data collection was immediately ceased.

2.5. Data analysis

With permission from the participant, all biomechanical data collected were analyzed using the Visual3D™ software. The position and orientation of each modeled body segment were calculated using six degree-of-freedom optimal tracking algorithms employed in Visual3D™ (Cereatti et al., 2006). Ankle and knee angles were computed as the orientation of the distal segment (e.g., foot) with respect to the adjacent proximal segment (e.g., shank) (Woltring, 1991) using the following Euler sequence: (i) flexion/extension (sagittal plane), (ii) ab/adduction (frontal plane), and (iii) axial rotation (transverse plane) (Cole et al., 1993). A “bottom-up” inverse dynamics approach was employed to compute instantaneous reaction forces and net joint moments when either the left or right foot was in contact with one of the force platforms. Segment body mass and inertial parameters incorporated in the inverse dynamics analyses were based on default procedures in Visual3D™; using published anthropometric data (Dempster, 1955) and geometric body segments.

The partial rupture of the AT presented as a culminating event (i.e., pain), which caused the incumbent firefighter to fall to the ground during the 37th trial of the hose-task. After reviewing the time-series biomechanical data for the trials preceding injury, there were two important insights into the mechanism of injury that may help to guide future injury prevention and reporting efforts. All data presented have been truncated to include the first stride of the movement, using the displacement of the whole body center of mass (initiation of movement) and the vertical ground reaction force measured from the left foot (termination defined as FV<10 N). To facilitate comparison across trials, kinematic and kinetic waveforms were time normalized to 101 data points (0 to 100% of movement) using a shape-preserving, piecewise cubic interpolation method implemented in MATLAB (Version 2012a, The MathWorks, Inc., Natick, MA, USA).

3. Results

3.1. Insight I: consider the full anatomical linkage

The firefighter's kinematics were altered beyond the site of injury. The right ankle and knee angles at the onset of the injury trial (i.e., before the culminating event) were comparable to the preceding 36 repetitions (Figs. 2 and 3). However, a noteworthy change (>3 SD computed from the preceding 36 trials) was observed in the left knee posture (across all three axes of motion) before the initiation of movement during the 37th trial (Fig. 4), which suggests that the participant may have adapted his movement behavior in response to a deviant load exposure in the preceding trial.

3.2. Insight II: consider the cumulative load (i.e., all movement patterns performed leading up to the culminating event)

The rope used to simulate the hose-advance task was connected to a weighted cable machine, thus requiring participants to walk backwards (under load) as they returned to the start position. Although the experiment was originally designed to evaluate participants' movement patterns during the advance phase of the task, by coincidence the data collection system was left running long enough to capture the return phase of most trials (30/36). Fortuitously, the participant contacted the in-ground force platform on the right side during the majority of these trials (29/30). Despite no apparent differences in the peak vertical ground reaction forces recorded during the stance phase of this backward motion, the participant was found to adopt a more deviated ankle posture (Fig. 5; increased dorsiflexion, inversion, and internal rotation) during the trials from the second test session (S2; 26–36). However, what is perhaps most intriguing was the fact that the participant's right frontal plane ankle moment was considerably higher (with opposing tendency to the previous trials) during the return phase of the trial performed immediately before the culminating event (Fig. 6; ~30% of the movement). Interestingly, the magnitude of the left foot vertical ground reaction forces during the initiation of the movement were comparable across all the preceding 36 trials leading up to the culminating event (Fig. 7).

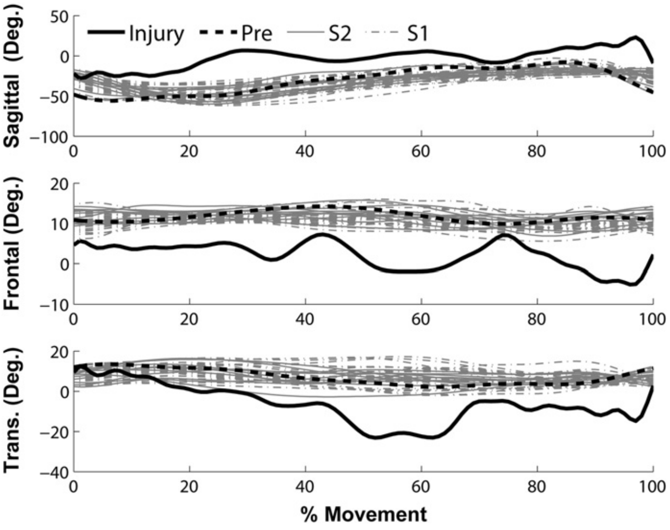

Fig. 2. Three-dimensional kinematics of the right ankle for the first stride of the hose-advance task. S1 = session 1 (trials 1–25); S2 = session 2 (trials 26–36).

4. Discussion

The unique and unexpected event described in this case report provides insight into the complexity of characterizing overexertion (i.e., acute) and overuse (i.e., cumulative) injury pathways. In most circumstances the firefighter's AT rupture would have been described as an acute injury, linked to overexertion during the culminating trial; however, based on the biomechanics data collected, it would appear that the magnitude of the applied load was not the sole mechanism

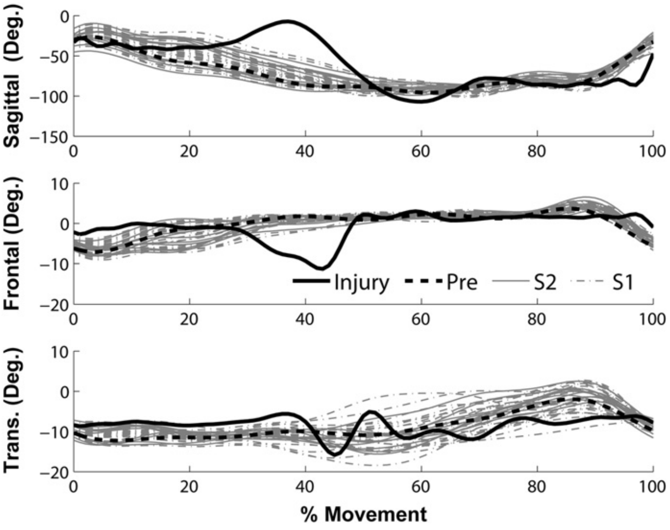

Fig. 3. Three-dimensional kinematics of the right knee for the first stride of the hose-advance task. S1 = session 1 (trials 1–25); S2 = session 2 (trials 26–36).

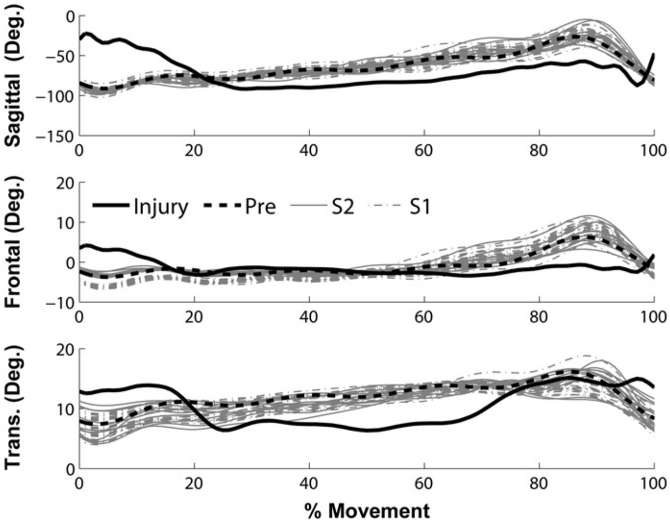

Fig. 4. Three-dimensional kinematics of the left knee for the first stride of the hose-advance task. S1 = session 1 (trials 1–25); S2 = session 2 (trials 26–36).

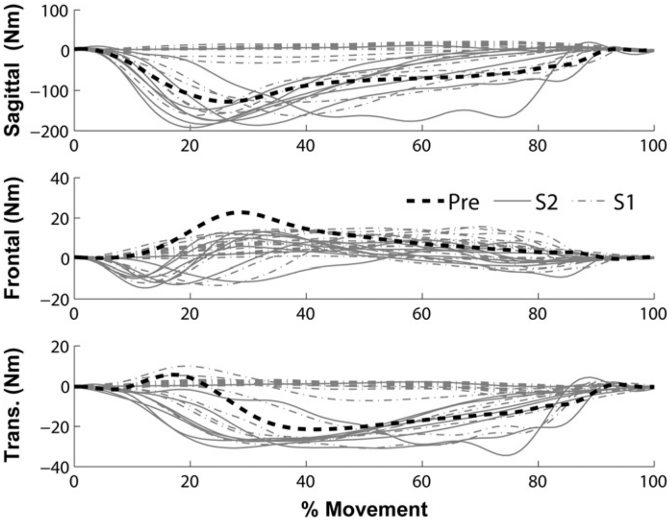

Fig. 6. Three-dimensional moment computed at the right ankle for the return phase of the hose-advance task during stance of the second backward stride. S1 = session 1 (trials 1–25); S2 = session 2 (trials 26–36).

for tissue failure, as would typically be the case with acute injury. Rather, the data lend support to the notion that the failure tolerance of the AT was modulated in response to the cumulative exposure to the simulated tasks, with the initiation of severe tissue damage occurring in backward phase of the preceding trial. This finding supports previous recommendations (Kumar, 2001; McGill, 1997), stating that focusing on a single variable (e.g., peak force), joint or culminating event may not provide a comprehensive understanding needed to avert future injury.

The AT is one of the most frequently injured tendons in the human body (Wren et al., 2001), even though it is considered to be one of the strongest and thickest tendons (Malvankar and Khan, 2011). The majority of AT ruptures are seen in men, with peak incidence occurring between 30 and 50 years of age (Leppilahti and Orava, 1998). The most common location for AT rupture is 3 to 6 cm proximal to the point of insertion on the calcaneus, due to the small cross-sectional area and reduced vascular supply in this region (Hess, 2010). This corresponds to the location of injury experienced by the incumbent firefighter.

Considering the short-term loading history of the participant's right lower-limb, it is noteworthy that the increased frontal plane moment that was measured at the ankle is a known risk factor for AT rupture (Hess, 2010). There are two plausible explanations for this increased loading scenario: (i) the failure tolerance of the AT was reduced due to repeated loading and when the increased moment was observed, the AT partially ruptured, thus changing both the magnitude and tendency of the ground reaction forces measured during right foot contact, with no changes in motion, or (ii) there was a change in movement behavior, potentially caused by fatigue, that resulted in an acute exposure to the AT sufficient to cause partial rupture. However, there is no evidence for fatigue, especially after listening to the firefighters once they completed the testing protocol. From a quantitative perspective, the data presented support the notion that the participant maintained form and did not gradually

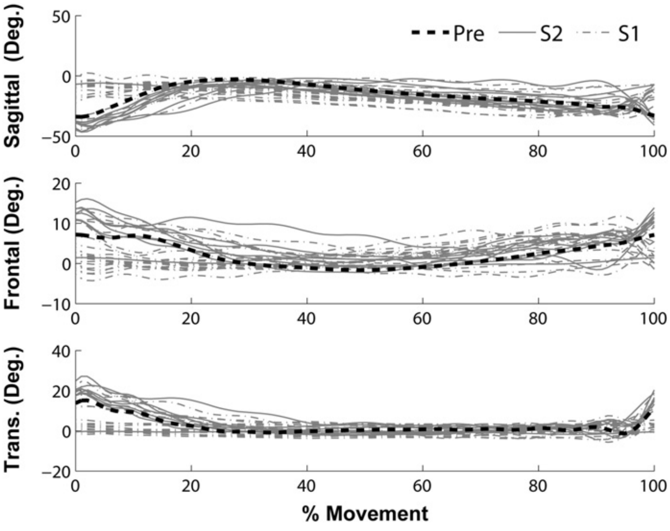

Fig. 5. Three-dimensional kinematics of the right ankle for the return phase of the hose-advance task during stance of the second backward stride. S1 = session 1 (trials 1–25); S2 = session 2 (trials 26–36).

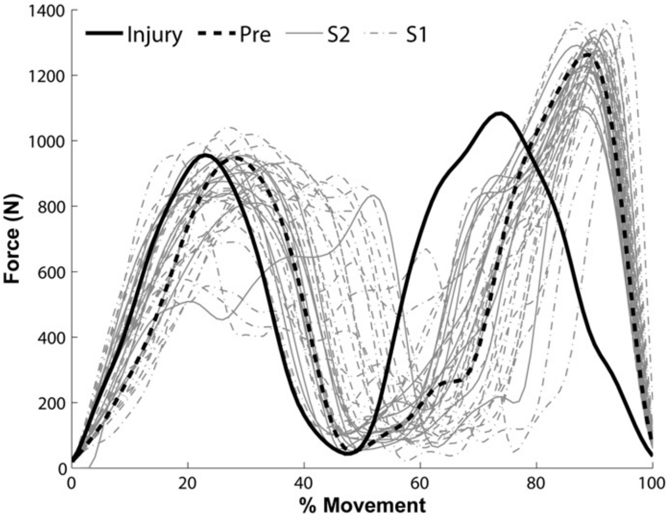

Fig. 7. Left side ground reaction forces during the initiation of the hose-advance task. S1 = session 1 (trials 1–25); S2 = session 2 (trials 26–36).

alter or adopt poor form when executing the simulated fire ground tasks, as there was very little variability in the lower limb mechanics between trials (1 through 36) leading up to the culminating event. An alternate hypothesis for the mechanism of injury may be that the altered starting position observed at the left knee during the injury trial may have imposed increased tissue stress on the right AT, thus causing injury.

Considering the biomechanics data that were captured during the culminating event, it is recommended that future efforts for the prevention and reporting of musculoskeletal injuries include guidelines to accommodate the complexities of tissue overload. Additionally, the nature (i.e., frequency, duration, magnitude, type) of all previous loading needs to be considered, both in the workplace, as well as during activities of daily living. Every individual lives with a unique set of physical demands that stem from the combination of their job-related and life-related tasks. For firefighters, these demands may reflect the skills necessary to safely suppress a live fire or effectively assist at the scene of an accident, but they also encompass those activities that each of them perform when they go home at the end of the day (e.g., going for a run, doing chores around the house, etc.). However, each of these activities can mitigate the failure tolerance of an individual's tissues, making it difficult to identify the mechanical exposure responsible for the injury marked by a culminating event. Considering the injury observed in this case report, since the magnitude of loading was similar across all trials, it is hypothesized that the mechanism for injury was not the result of a single aberrant loading situation. As such, it would be difficult to assert that the laboratory tasks were the sole cause of the AT injury, given the possible influence of loading history.

The present work is limited by the absence of joint load and moment data for the right ankle and knee when the injury occurred, as the right foot never contacted the force platform during the second stride of the forward motion. As such, the data presented in this paper may not be sufficient to elucidate the true mechanism for the tendon rupture. However, this is largely due to the experiment's focus on characterizing the physical demands of simulated fire ground tasks. The magnitude of the left foot vertical ground reaction forces during the initiation of the movement were comparable across all the preceding 36 trials leading up to the culminating event (Fig. 7), the angular position of the right ankle and knee during right foot stance of the second stride were comparable (Figs. 2 and 3), and the hose-advance task was performed by a sample of 70 other incumbent firefighters with no incidence of injury. Each one of these observations provide further evidence to suggest that the injury sustained was likely the result of a cumulative exposure to sub-maximal loading.

It is important to highlight that although the participant donned his own athletic shoes for the study, this is not the typical footwear worn by firefighters on the fire ground. As such, it is important to acknowledge this potential limitation and influence that a change from boots to athletic shoes may have bearing on the mechanism of injury. However, between jurisdictions there is no standard issue footwear adopted by all firefighters. Moreover, our initial research question did not seek to quantify the effects of firefighters' equipment on their biomechanics.

5. Conclusion

Central to the insights obtained in this case report, is the notion that all tissue based musculoskeletal injuries are mechanical in nature (Kumar, 2001; McGill, 1997). The unexpected and rare event that was captured in this work provides insight into the complexity of characterizing overexertion from cumulative injury pathways. It is recommended that future efforts in injury prevention and reporting consider an individual's physical demands (both at work and in life) and document the nature (i.e., frequency, duration, magnitude, type) of loading when considering the mechanism of injury.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.clinbiomech.2013.02.002.

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