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Evaluating the Reliability of a Marker-Less, Digital Video Analysis Approach to Characterize Fire-fighter Trunk and Knee Postures During a Lift Task: A Proof-of-Concept Study

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Abstract

Background: Valid and reliable postural assessment tools can better support injury prevention strategies. 3-dimensional movement analysis as the gold standard to assess human movement is often not feasible in applied, occupational settings. For example, heavy lifting associated with known injury risk factors is impacted when performed by fire-fighters wearing personal protective equipment (PPE). Task simulations including PPE complicate postural assessment methods. Consequently, the study purposes were: a) To establish proof-of-concept using Dartfish movement analysis software to measure fire-fighters' trunk and knee postures during a fire-fighting lift task while wearing PPE and b) To establish the reliability of this approach.

Methods: A sample of twelve active-duty fire-fighters lifted a high-rise pack from floor to shoulder level. Frontal and sagittal trunk and knee flexion angles and hip vertical displacement were measured using Dartfish. All measurements were repeated on a second day for reliability analysis. Descriptive statistics characterized fire-fighter lower extremity postures. Intra-class correlation coefficients, standard error of measurement and minimal detectable change determined reliability of trunk and knee angles and hip displacement measures.

Results: Fire-fighters demonstrated 150° ± 12° of left knee flexion, 150° ± 13° of right knee flexion and 98° ± 17° of trunk flexion when lifting a high-rise pack from floor to shoulder level. Hip vertical displacement was 19% ± 8% when normalized to the individual's height. Absolute reliability results indicated that fire-fighter knee postures could be assessed within 5° and trunk postures within 9° when using Dartfish.

Conclusion: Although measurement reliability of trunk and knee angles was comparable to previous studies, accuracy limitations and methodological challenges were identified. Protocol recommendations to optimize reliability and interpretability include focusing on using positional coordinates to identify hip displacement; further research to validate this approach is suggested. Implications include measuring impacts of ergonomic interventions designed to modify fire-fighter task performance strategies in response to known injury risk factors.

Keywords: Lower extremity postural analysis; Dartfish; Fire-fighting; Lifting

Introduction

Fire-fighters perform physically demanding, non-cyclical work tasks in challenging environments resulting in increased exposure to risk factors associated with musculoskeletal injury [1-4] where soft tissue injuries due to overexertion are the most frequently reported injury type and mechanism [3,5-7]. Although the specific mechanism linking job factors and injury rates is unclear, previous research has shown that the high physical loads associated with fire-fighting tasks predispose fire-fighters to increased risk of injury [5]. Furthermore, tasks associated with fire-fighting such as heavy lifting and unsafe work postures [1,3] as well as awkward postures and body motion [4,8] have been associated with higher injury rates amongst fire-fighters. Developing postural assessment tools that can be used in applied, occupational contexts such as fire-fighting will aid development and implementation of injury prevention strategies positioned to mitigate these risk factors associated with injury.

Although previous studies [9,10] have measured fire-fighters' movement and physical ability while performing fire-fighting tasks, the protocols were lab-based simulations that controlled measurement of outcomes which limited ability to extend findings to an applied context. Conducting ergonomic research requires consideration of the applied context as factors specific to the work environment can impact the way work tasks are performed. For example, in addition to the

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physically demanding aspects of their work, fire-fighters are required to wear personal protective equipment referred to as bunker gear that weighs in excess of 40 kg. In addition to the additive carriage load, the bunker gear changes the way fire-fighters perform their work tasks, in particular their gait and balance [11-13]. A recent study [14] found that fire-fighters' boots decreased lower body range of motion in the sagittal and transverse planes where a greater reduction in ankle and forefoot range-of-motion was observed in female compared to male fire-fighters, implying higher risk of foot and ankle injuries amongst female fire-fighters compared to male fire-fighters. These study findings suggest that including fire-fighter bunker gear is an important consideration when assessing fire-fighter kinematics and when attempting to understand the relationship between task performance strategies and injury risk. However, conducting movement analysis while fire-fighters wear their required PPE becomes challenging particularly when utilizing three dimensional (3D) motion capture systems, the gold standard in measuring kinematics. 3D motion capture systems are expensive, require significant expertise, utilize skin-based marker sets and require a non-reflective data collection space to enable valid, reliable analysis and data processing. These considerations make 3D motion capture impractical for conducting ergonomic assessments of fire-fighters performing fire-fighting tasks particularly when retaining the ecological validity of the study findings to improve understanding of the relationship between posture, task performance and injury amongst fire-fighters, is important.

One potential approach to identify the relationship between task performance strategies and risk factors associated with MSD [15,16] in applied, occupational contexts is using marker-less, video-based inputs. Although video is limited to two-dimensional analysis, adapting video analysis to this context would enable fire-fighters to wear their bunker gear and extend data collection to various applied occupational environments. Developing an approach to reduce reliance on subjective evaluations often utilized to categorize work postures based on video-data would improve reliability and validity of determinations made based on these measurements. The limitations associated with subjective evaluations of work postures are augmented by the limited number and accessible methods available for assessing task performance and work postures from video-based inputs [15,17]. One approach that might be adapted for this application is DARTFISH movement analysis software (Lausanne, Switzerland).

Dartfish enables kinematic analysis using video-based inputs from a variety of sources. Dartfish has been widely used to provide performance-based feedback to athletes as well as in kinematic research measuring lower extremity postures during functional tasks such as lifting, running, walking and squatting. High to moderate inter- and intra-rater reliability has been established when using Dartfish to analyse knee and hip angles postures during lifting [18], squatting [19], jumping [20,21] and running [18,19,22–24] in controlled, laboratory settings. Studies have also established concurrent validity of Dartfish compared to 3-D motion capture systems when analyzing hip and knee kinematics from video positioned in the frontal plane during running [24] hip and knee angles measured in the sagittal plane during squatting [25]. Based on these results, it has been suggested that Dartfish has potential to be applied to studies involving more complex movements [25].

An important consideration is that previous Dartfish studies have often been conducted in laboratory settings and have adopted methods commonly used to optimize data accuracy in 3D motion capture. For example, although not required when using Dartfish software, previous studies [18,19,21,22,24,25] have used skin-based markers to improve reliability during data processing. In applied occupational contexts where workers are frequently required to wear personal protective equipment (PPE) that impacts task performance strategies, it is not feasible to utilize skin-based markers. Furthermore, research using Dartfish has confined movements to single planes [18,19,22-25] which facilitates accurate kinematic measures but is not a feasible approach for applied movement analysis where workers perform multi-planar movements and postures.

Eltoukhy et al. [25] suggested that Dartfish has potential to be applied in kinematic analysis of multi-planar movements where minimizing the use of markers could improve the quality of values. One approach may be to use x,y positional co-ordinates to track body segments rather than angle tracking, both available in Dartfish software. Angle tracking requires tracking of three markers however tracking x,y positional co-ordinates requires tracking of only one marker. An important consideration is that x,y coordinates of a body segment are not clinically meaningful in isolation, consequently converting positional displacement to an anthropometric reference may improve the clinical relevance of this outcome. Investigating whether Dartfish analysis can be applied to multi-planar movements in populations where context limits feasibility of skin-based markers and retain measurement properties established during previous studies, requires future research. Furthermore, determining whether previously established reliability can be achieved using a marker-less approach that would be adopted in applied, ergonomic contexts, has yet to be explored. Implementing Dartfish in a proof-of-concept study will allow exploration of feasibility of a marker-less approach to identify postures associated with occupational tasks and feasibility of multiple analytical approaches including angle and vertical displacement, before further developing this approach for application to larger samples and more complex occupational tasks.

Consequently, the primary objectives were to conduct a proof-of-concept study for using video-based inputs of firefighters lifting a high-rise pack from floor to shoulder while wearing full bunker gear and to: 1) Identify firefighters' trunk and knee angles and hip vertical displacement during this lift task and 2) Examine the reliability of three Dartfish analytic methods (angle tracking, positional co-ordinate tracking and single frame analysis) of firefighter lower body postures while using a marker-less approach.

Methods

Context

To investigate the utility of this posture analytical approach in an occupational context, all study components were conducted in the fire-fighter's training facility allowing use of fire-fighting equipment and tools during the lift task. The training facility accommodates entry of four fire trucks and supports facilities and equipment that enables implementation of field-based fire-fighting task protocols.

Participants

A single fire service in South-western, Ontario (N=471 full time fire-fighters; n=13 female fire-fighters) is the research partner with which we have an established on-going program of research. A simple random selection process was utilized to identify a sub-sample (n=6) of male fire-fighters (mean age 45 ± 8.6 years; stature 1.77 ± 0.12 m; body mass 92.4 ± 5.6 kg) from a sample (n=42) of male fire-fighters

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who participated in larger study to identify factors associated with fire-fighter work health. All female fire-fighters (n=6) who participated in larger study were included in the current analyses (mean age 36 ± 5.4 years; stature 1.62 ± 0.04 m; body mass 67.4 ± 12.6 kg.). Participant characteristics are reported in Table 1. Fire-fighter participants were required to hold fully active status (i.e., free of any condition that limited assignment to full duty) within the fire department. Prior to data collection, all fire-fighter participants provided written consent following review of the study purpose and data collection procedures. Ethics approval was obtained through the university research ethics board.

	Age (years)	Height (m)	Weight (kg)	Tenure (years)
Male (n=6)	45 (8.6)	1.77 (0.12)	92.4 (5.6)	16.3 (7.8)
Female (n=6)	36 (5.4)	1.62 (0.04)	67.4 (12.6)	7.0 (3.6)
Overall (n=12)	40.5 (8.3)	1.72 (0.10)	79.9 (16.0)	11.7 (7.6)

Table 1: Participant demographics. All values reported as Mean (SD).

Protocol

Upon arrival, participant demographic and anthropometric measures were obtained following which participants were requested to don all fire-fighter bunker gear (22.7 kg) including self-contained breathing apparatus (SCBA) (18.1 kg). Participants were then asked to stand in anatomical position at a designated start position, marked on the floor with tape as a box measuring 0.4 m x 0.3 m, facing the frontal camera position. Participants were then instructed to lift a high-rise pack (HRP) to their shoulder and take 3 forward steps. Participants were permitted to move out of the "start box" as deemed necessary to lift the HRP. Participants were asked to perform the task as they would in a typical emergency response situation.

The placement of the HRP on the floor was standardized to the right of each participant. The HRP (19.5 kg) consisted of two lengths of fire-fighting hose (15 m each; 30 m total) including an attached nozzle and tools (i.e., wrench, couplings and other equipment). Lifting and carrying a HRP is required when fire-fighters respond to structural fires (i.e., large warehouses, high rise) that contain hose cabinets and/or stand pipe systems and was deemed a physically demanding, high-risk task by our fire-fighter research partner.

Two-dimensional frontal and sagittal plane trunk and knee kinematic data were captured using two digital video cameras (JVC HD Everio GZ-VX700, Full HD, AVCHD), positioned on individual tripods facing the frontal and sagittal planes of movement. The sagittal camera was positioned at a height of 1.5 m from the floor to the center of the camera lens and a horizontal distance of 4.9 m from the center of the participant's start position. The frontal camera position was positioned at a height of 1.4 m from the floor to the center of the camera lens and a horizontal distance of 4.2 m from the center of the participants' start position.

Data reduction

The audio-video interleaves (AVI) files from the sagittal and frontal plane video cameras were downloaded and analyzed separately in Dartfish Prosuite software (v. 5.5) using three methods; (i) angle tracking (ii) positional co-ordinate tracking and (iii) single frame analysis. Two-dimensional analysis using Dartfish software has been previously validated to quantify lower limb kinematics [22,24,25]. The following describes the data reduction process corresponding to each of these methods, from both the sagittal and frontal plane video positions and methods used to define trunk and knee angles. The same researcher conducted all data reduction and analysis.

Angle tracking: The angle tracking data reduction method involved measuring, tracking and recording trunk and knee angles throughout the lift task. Trunk and knee angles were measured separately from the first frame at which the participant initiated movement from anatomical start position to the frame when the participant made initial heel strike during the first forward step. Both points of reference were determined by watching the video frame by frame.

The 'angle drawing tool' and 'data table' were selected and linked to enable automatic entry and tracking of the hip and knee angles in the data table. The 'auto-track' feature was set at 'fast' (monitoring 20% of the video image); trunk and knee angles were then tracked automatically by selecting 'play'. The tracked trunk and knee angles and corresponding time were simultaneously and automatically recorded into the data table, by the software, every 0.03 second. The markers often deviated from the established landmarks requiring a manual correction presenting a methodological challenge using the auto-tracker feature. When this occurred, the tracking feature was suspended, the incorrect angle was removed from the data table, the video was rewound to the frame where the error occurred and the angle-tracking feature was re-activated. The trunk and knee angles were defined using the following conventions.

Defining trunk and knee angle: Because anatomical markers could not be applied to fire-fighter bunker gear, defining characteristics on fire-fighter equipment were used to identify placement of the Dartfish markers used to create postural angles. Relative angles were measured where the angle of interest was measured between the long axis of one body segment and the long axis of the adjacent body segment at the joint of interest from the established vertex. The angles were measured using a 180° scale; angles less than 180° were classified as flexion and more than 180° were classified as extension. As participants started in anatomical position facing the video camera positioned in the frontal plane and rotated clockwise towards the video camera positioned in the sagittal plane, angles obtained from the frontal camera refer to the left body side and sagittal camera analysis were conducted on the right body side.

When viewed from the frontal camera, left trunk angle was identified as the angle formed by positioning one marker as the vertex on the left hip, using the top reflective stripe of the bunker coat as a reference. One line connected this marker to the lateral aspect of the left shoulder, using the Canadian flag on the bunker coat as a reference, and a second line connecting the vertex with the lateral aspect of the participant's left knee (see Figure 1).

Right trunk angle viewed from the sagittal plane camera was formed by connecting markers placed at the lateral aspect of the right "shoulder" with the vertex established at the right hip, using the bottom reflective stripe of the bunker coat as a reference, and a second line connecting the vertex with the lateral aspect of the right knee (see Figure 2).

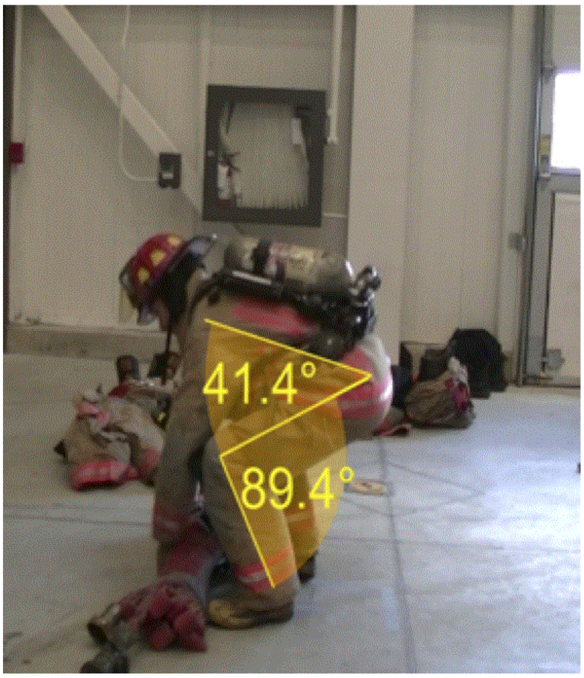

Figure 1: Left trunk and knee angle measures from the frontal plane camera.

Figure 2: Right trunk and knee angle measures from the sagittal camera plane.

When viewed from the frontal camera, left knee flexion angle was defined by using a marker placed at the lateral aspect of the participant's left foot using the bottom reflective pant stripe as a reference, with the vertex established by placing a marker at the lateral aspect of the left knee and a second line connecting the vertex with a maker placed at the lateral aspect of the left hip, using the bottom stripe on the coat as a reference (see Figure 1). The same landmarks were used to identify knee frontal angle from the sagittal camera perspective but in reference to the participants' right lower extremity (see Figure 2). The data table, containing the individual participants' tracked trunk and knee angles was exported into separate Excel spreadsheets. Participant's tracked trunk and knee angles were consolidated and imported into SPSS for statistical analyses.

Positional coordinate tracking

Positional co-ordinate tracking required placing a marker on a specific point of reference in the video which provided information about the horizontal and vertical displacement of that marker when using the same tracking methods described in angle tracking. For the purposes of this proof-of-concept model, we focussed on vertical displacement of the hip. In both sagittal and frontal camera positions, the top stripe on the coat of the bunker gear was used to standardize trunk marker placement as an estimate of the hip location (see Figure 3). An object of known length was used to calibrate the video images converting the y-coordinate data into meaningful units of measurement. The data table containing all y-coordinates of hip displacement throughout the lift task was exported into a Microsoft Excel spread sheet. Individual participant trunk y-coordinate data were consolidated into one file and imported into SPSS for statistical analyses.

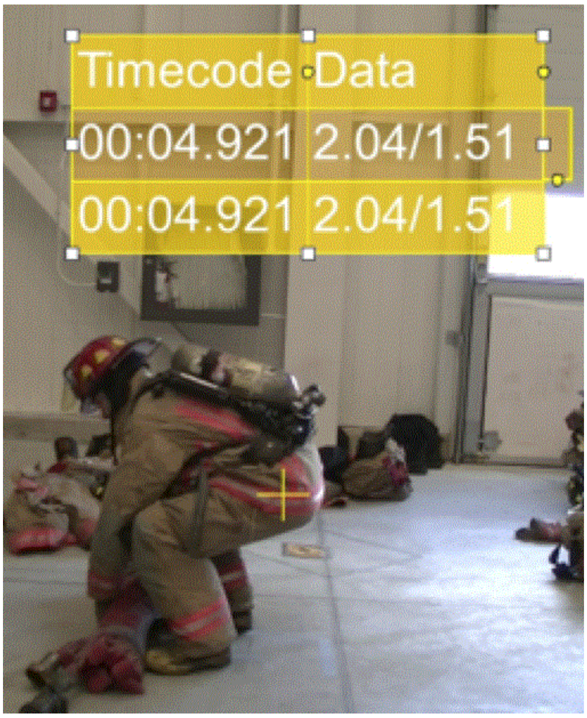

Figure 3: Hip co-ordinate marker placement for measuring hip vertical displacement from frontal plane camera.

Single frame analysis

Single frame analyses were conducted to determine peak trunk and knee postures during task transitions or during high-risk postures deemed as deviations from neutral postures [26-29]. Trunk and knee angles were defined using the same conventions as used during the angle tracking condition. Sagittal and frontal camera positions required different methods to extract single frame angles due to changes in participant position and orientation during task performance in the video frame.

(a) Frontal Camera Position: Visual frame-by-frame inspection was used to identify the frame when the participant's left hand first contacted the high-rise pack. This was identified as a critical phase in the lift task where transfer of the high-rise pack from floor to shoulder was initiated. Once this video frame was identified and recorded, participant left-side trunk and knee flexion angles were measured using the angle drawing tool in the analyser module. The relative left trunk and knee flexion angles were recorded in SPSS for statistical analyses.

(b) Sagittal Camera Position: The frame used in the frontal camera position could not be used when viewed from the sagittal camera, as the trunk and knee were not positioned perpendicular to the frontal camera; consequently a different frame needed to be identified. However, the point in the lift task when the HRP was at its highest vertical position provided adequate sagittal views of the trunk and knee. Consequently, participant right-side trunk and knee angles at this point in the lift posture were analyzed. The highest vertical point of the HRP was calculated using a marker placed on the HRP determining the frame with the highest vertical displacement. The video was played to this video frame in the Dartfish analyzer. The angle drawing tool was used to measure trunk and knee angles associated with this posture. The relative right trunk and knee angles were recorded in SPSS for analyses.

Data analysis

To identify fire-fighters' trunk and knee flexion angles and hip vertical displacements, descriptive statistics including trunk and knee flexion mean, minimum and maximum angles and the corresponding standard deviation were determined from both angle tracking and the single frame analytical methods and from both sagittal and frontal plane video cameras. To determine hip vertical displacement, the mean, standard deviation, maximum and minimum of y-coordinate hip position were calculated from both sagittal and frontal plane video cameras. To improve clinical utility of this outcome, the difference between maximum and minimum vertical hip displacement was calculated and normalized to participant height to yield relative hip vertical displacement. For ease of interpretation, only hip relative vertical displacement results are presented. Smaller relative vertical displacements represented less vertical hip displacement and larger relative vertical displacements were associated with more vertical hip displacement.

Videos of all participants for all kinematic outcomes and data reduction methods (angle tracking, relative hip vertical displacement from both camera positions, were analysed twice by the same tester to determine the intra-rater reliability. The average interval between measurements was 1.5 months. The mean values of the angle tracking and hip vertical displacement were used to calculate relative estimates of intra-rater reliability using intra-class correlation coefficients for absolute agreement (ICC2,1) [30]. Reliability coefficients were interpreted according to subjective categories [31] in which 0.4 were considered unacceptable, 0.41 to 0.60 moderate, 0.61 to 0.8 substantial and 0.81 to 1.0 excellent. Standard error of the measure (SEM) and minimal detectable difference (MDC) were calculated as estimates of absolute reliability. SEM, as an estimate of measurement error in angle (degrees) and positional co-ordinate (meters) was calculated using the following formula: SD (average) $\sqrt{1-ICC}$ [32]. $MDC_{90} = SEM \times \sqrt{2} \times 1.65$ [33] was used to measure the amount of change in angle or positional co-ordinates required for an evaluator to be 90% certain the change was beyond the threshold due to measurement error.

Descriptive statistics and intra-rater reliability analyses were performed using the Statistical Package for the Social Sciences version 19 (SPSS Inc., Chicago, Illinois, USA). Standard error of the measure (SEM) and the minimal detectable change (MDC) were calculated in Microsoft Excel, 2011 (version 14.4.6).

Results

Demographics

The participant sample (n=12) for this study represented male (n=6) and female active fire-fighters with a mean age of 40.5 ± 8.3 years and 11.7 ± 7.6 years of fire-fighting service. Gender-stratified analyses of demographics indicate that male fire-fighters were generally older, of larger stature and had more years of service than their female counterparts (see Table 1). Male fire-fighters held the rank of Fire-fighter (67%) and Captain (33%); 100% of female participants held the rank of Fire-fighter.

Trunk and knee posture analysis

Descriptive statistics of trunk and knee postural analysis using angle tracking, positional tracking and single frame analyses from both frontal and sagittal camera perspectives are shown in Tables 2 and 3 respectively. A gender-stratified analysis demonstrating male and female fire-fighter lower extremity kinematics is reported in Table 4. The following results are based on the calculated mean and standard deviation of trunk and knee kinematics of occasion 1 and occasion 2.

	Occasion 1 (n=12)		**Occasion 2 (n=12)**	
Posture	**Mean (SD)**	**Max./Min.**	**Mean(SD)**	**Max./Min.**
Knee angle (°): Tracked	148.4 (12.1)	179.9/81.2	152.0 (11.2)	180.0/81.3
Trunk angle (°): Tracked	100.2 (15.4)	179.6/37.7	96.8 (18.4)	179.8/33.5
Relative Hip Vertical Displacement (%)	17.8 (4.1)	23/8	17.5 (4.8)	25/8

Trunk angle (°): Single Frame	57.2 (14.1)	89.5/40.2	56.1 (14.5)	86.4/37.2
Knee angle (°): Single Frame	113.1 (27.4)	168.2/80.7	110.6 (26.9)	164.2/78.3
Mean and SD represent the mean of the participant mean values. 'Max' represents the maximum posture; 'min' represents the minimum posture in the posture range.				

Table 2: Frontal camera: Left lower extremity postures.

Posture	Occasion 1 (n=12)		Occasion 2 (n=12)	
	Mean (SD)	Max./Min.	Mean (SD)	Max./Min.
Knee angle (°): Tracked	147.7 (13.5)	180.0/24.0	149.0 (12.7)	179.8/36.4
Trunk angle (°): Tracked	139.9 (20.0)	179.0/25.8	149.2 (17.2)	180.0/19.4
Relative Hip Vertical Displacement (%)	20.4 (14.4)	46/4	18.8 (11.4)	44/6
Trunk angle (°): Single Frame	166.2 (7.2)	173.8/147.4	168.5 (6.0)	175.0/154.3
Knee angle (°): Single Frame	148.2 (20.3)	175.4/93.7	149.2 (25.4)	170.9/72.6
Mean and SD represent the mean of the participant mean values. 'Max' represents the maximum posture; 'min' represents the minimum posture in the posture range.				

Table 3: Sagittal camera: Right lower extremity postures.

Posture	Frontal Camera: Left Lower Extremity Postures		Sagittal Camera: Right Lower Extremity Postures	
	Male (n=6)	Female (n=6)	Male (n=6)	Female (n=6)
Knee angle (°): Tracked	150.5 (15.7)	150.0 (5.8)	144.8 (16.3)	151.8 (7.2)
Trunk angle (°): Tracked	94.2 (16.0)	102.9 (16.8)	145.8 (11.7)	143.2 (24.6)
Relative Hip Vertical Displacement (%)	16.2 (5.0)	19.1 (3.2)	20.3 (14.2)	18.3 (11.6)
Trunk angle (°): Single Frame	54.4 (9.5)	58.8 (17.6)	169.7 (3.6)	167.5 (13.7)
Knee angle (°): Single Frame	120.6 (33.3)	103.0 (14.0)	142.9 (29.9)	154.6 (9.3)
Mean (SD) represent the mean of the participant mean values. Data represents combined Occasion 1 and Occasion 2 outcomes.				

Table 4: Gender stratified analysis of lower extremity postures.

Trunk posture

When tracking trunk angle throughout the lift task viewed from the frontal camera, the overall mean left trunk flexion was 98.5° ± 16.7°; maximum was 179.7° and minimum was 35.6°. The average relative change in left hip movement was 17.6% ± 4.4% of participant height. Peak mean trunk posture at the lowest point of the lift was 56.6° ± 14.0°. Female fire-fighters demonstrated less trunk flexion (102° ± 16.8°) compared to male fire-fighters (94.2° ± 16.0°) throughout the lifting task and more relative hip displacement (19.1% ± 3.2 versus 16.2% ± 5.0%).

When tracking trunk angle throughout the lift task viewed from the sagittal camera, participant mean right hip flexion angle was 144.5° ± 18.8°; maximum was 179.7° and minimum was 22.6°. The average relative change in right hip movement was 19.6% ± 12.7% of participant height. The peak mean right hip angle when transferring the high-rise pack to shoulder height, determined from single-frame analyses was 167.3° ± 6.6°.

Knee posture

When tracking knee angle through the lift task from the frontal camera position the mean left knee flexion was 150.2° ± 11.5°; maximum was 180° and minimum was 81.3°. The peak mean left knee posture determined from single frame analyses, at the lowest point of the lift was 111.8° ± 26.5°. When tracking knee frontal angle through the lift viewed from the sagittal camera the mean right knee angle was 148.3° ± 12.8°; maximum was 179.9 and minimum was 30.2. The peak mean right knee angle when transferring the high-rise pack to shoulder height was 148.7° ± 22.4°. Male and female fire-fighters demonstrated similar left knee angle however female fire-fighters demonstrated less knee flexion (151.8° ± 7.2°) compared to their male counterparts (144.8° ± 16.3°).

Reliability

Reliability of determining trunk and knee postural measures when viewing the fire-fighter lift task from the frontal and sagittal camera is reported in Tables 5 and 6 respectively.

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Intra-rater reliability

As shown in Table 5, intra-rater reliability was excellent (ICC2, 1=0.85-0.97) when using the angle tracking and single frame data extraction to identify left knee postures but was substantial (ICC2, 1=0.72) when using the angle tracking to determine trunk postures. However intra-rater reliability improved when measuring left hip relative vertical displacement and peak trunk posture from single frame analysis (ICC2, 1=0.84–0.97).

Table 6 shows excellent intra-rater reliability (ICC2, 1=0.93-0.94) for determining right knee postures when using angle tracking and determining peak knee posture. Intra-rater reliability for right hip postures was excellent (ICC2, 1=0.81-0.98) when using angle tracking and determining hip relative vertical displacement; determining peak right hip posture was associated with substantial (ICC2, 1=0.78) reliability.

Posture	ICC2, 1	95% CI	SEM	MDC90
Knee Angle	0.85	0.50, 0.96	4.5°	10.5°
Trunk Angle (Tracked)	0.72	0.30, 0.91	8.9°	20.8°
Relative Hip Movement	0.84	0.52, 0.95	2%	5%
Trunk Angle (single frame)	0.97	0.89, 0.99	2.5°	5.8°
Knee Angle (single frame)	0.97	0.91, 0.99	2.6°	6.1°
Reliability analyses were conducted with individual, combined (male and female) participant data.				

Table 5: Frontal Camera: Relative and absolute reliability of left lower extremity postures.

Posture	ICC2,1	95% CI	SEM	MDC90
Knee Angle (tracked)	0.93	0.78, 0.98	3.5°	8.2°
Trunk Angle (tracked)	0.82	0.51, 0.96	7.9°	18.4°
Relative Hip Movement	0.81	0.48, 0.94	6%	13%
Trunk Angle (single frame)	0.78	0.36, 0.93	1.4°	3.3°
Knee Angle (single frame)	0.94	0.79, 0.98	5.6°	13.1°
Reliability analyses were conducted with individual, combined (male and female) participant data.				

Table 6: Sagittal Camera: Relative and absolute reliability of right lower extremity postures.

Absolute reliability

As shown in Table 5, absolute reliability measured using SEM and MDC are higher when determining left knee and hip postures using angle tracking than when determining peak left trunk and knee posture using a single video frame. Table 6 shows that absolute reliability is smaller when using angle tracking to determine right knee postures using angle tracking than when determining right-side trunk postures. The SEM and MDC are smaller when determining right peak trunk posture than right peak knee posture. Determining left and right hip relative vertical displacement is associated with low levels of absolute reliability although using a sagittal facing camera to determine right hip displacement results in higher absolute reliability compared to left hip displacement measured from the frontal camera position.

Discussion

This study determined that video-based movement analysis of fire-fighters trunk and knee postures while lifting a high-rise pack from floor to shoulder wearing full bunker gear was feasible using a novel measurement approach and Dartfish software. The key study findings include: 1) Fire-fighters require a range of trunk and knee postures to lift a high-rise pack from floor to shoulder however the accuracy of these measures requires further validation; 2) Intra-rater reliability was found to be substantial for measuring trunk angles and excellent when determining knee angles; hip vertical displacement was associated with excellent to moderate intra-rater reliability and 3) Fire-fighter trunk postures could be assessed within reasonable error margins (9°) and for knee postures within 5°. These findings are each discussed below.

Lower extremity postures characterized using Dartfish

When considering knee range-of-motion, fire-fighters demonstrated a maximum 180° of knee flexion in camera planes, a minimum 81° of left knee flexion and a minimum of 30° of right frontal knee motion to lift the high-rise pack from floor to shoulder. These results suggest that fire-fighters require between 100° and 150° of knee range-of-motion to perform this task. Furthermore, there appears to be a gender-specific effect where female fire-fighters demonstrate more vertical hip displacement and less trunk flexion compared to male fire-fighters. In addition to possible gender-specific task performance strategies, these outcomes provide preliminary task-specific, range-of-motion guidelines when considering rehabilitation goals of fire-fighters following possible lower extremity injury. However, when reviewing trunk angles from the sagittal and frontal camera planes, there is a noted discrepancy. For example, the combined mean of occasion 1 and occasion 2 left trunk angle was 98.4° compared to 144° of right trunk angle, calling into question the measurement accuracy of this approach. Furthermore, reliability measures of left trunk flexion (98°; SEM=8.9°; MDC=20.8°) and right trunk flexion (144°; SEM=7.9°; MDC=18.4°) suggest high measurement error as the 46° difference between left and right trunk flexion extends beyond the error of measure calculated. Consequently, it is highly likely that trunk angles measured from the sagittal camera using a frontal plane of view may not be accurate. Although previous research has validated Dartfish to a 3D gold standard [24,25], the same research also found no statistically significant correlation between the 2D and 3D right peak knee abduction angle or pelvic drop angle during a jumping task [24]. These results in combination, suggest that hip and knee angles measured from a frontal perspective using a 2D measurement approach should be interpreted with caution. Our study results suggest that further research comparing angles obtained from 2D analysis to 3D systems during multi-planar movements as required during the current lifting task is recommended before extending Dartfish angle analysis to field applications of postural assessment.

In addition to tracking trunk and knee angles throughout the lifting task, peak trunk and knee postures from a single video frame at a single reference point in task performance were also determined. Previous studies [18,21,22] have also used specific points during task performance to identify lower extremity postures. The purpose of including this single-frame analysis was to determine whether this approach was associated with less methodological challenges and higher reliability than the angle tracking. Our study findings

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confirmed trunk and knee postures using this approach were associated with acceptable levels of absolute and relative reliability and less measurement error when compared to tracking knee and trunk angles. Furthermore, the methodological challenges of tracking angles throughout the tasks such as marker occlusion were not observed when measuring angles at a single frame. Notable however is the wide confidence interval associated with the intra-class correlation coefficient when measuring right trunk posture during the single-frame analysis (ICC2,1=0.78, CI95%=0.36, 0.93). This may be the result of methodological challenges previously discussed with accurately determining trunk postures from the sagittal camera perspective or a reflection of our small sample size. Although this approach appears more feasible than angle tracking, an important consideration is that using a single frame of reference only provides information about the peak posture associated with a particular task; it is unable to provide information related to the dynamics of the task (i.e., maximum, minimum, range of movement) that tracking angles or anatomical positional tracking enables.

Although not considered in previous Dartfish research, in anticipation of limitations with analyzing body segment angles using 2D systems, anatomical positional tracking was used to determine relative hip vertical displacement. Preliminary evidence suggests that positional co-ordinates may be a preferred method of measuring postures during multi-planar movements. For example, when reviewing relative hip vertical displacement compared to task ergonomics, the results suggest that fire-fighters moved less than one third of body height (18% of height). In terms of knee and hip mechanics, this finding suggests participants used less knee flexion and more hip flexion (i.e., “bending at the waist” versus “bending at the knees”) when lifting the high-rise pack from floor to shoulder. The ergonomic implications of this analysis are further supported when considering left-side relative hip displacement (19%) in comparison to left trunk flexion (98°) and average left knee flexion (150°). The 19% relative hip displacement suggests tasks were performed with moderate knee flexion where higher levels of knee flexion (i.e., less than 90°) would be associated with larger hip displacements. For example, 90° knee flexion would likely be associated with 50% hip displacement. Consequently, 19% hip displacement suggests moderate knee flexion and subsequently, more trunk flexion to reach the floor where the high-rise pack was positioned. These results suggest that relative hip movement as a single construct of lower extremity posture might provide as much information about lower extremity posture as knee and trunk angle kinematics considered individually. However further research to understand both clinical applicability and validation of relative hip vertical displacement to lower extremity kinematics is required before further application.

Reliability

Acceptable levels of reliability were measured when determining trunk and knee postures from video-based inputs using angle tracking, hip relative vertical displacement and peak trunk and knee postures. These results extend previous research [18,22] that also identified acceptable levels of reliability when measuring lower extremity kinematics using the same software. However, the current research is unique as acceptable levels of reliability were achieved with fewer process controls enabling consideration for exploration in further applied contexts. For example, although previous studies using this software also used video-based inputs, skin-based markers were used to facilitate data processing and movements were confined to a sagittal plane of reference. Participants in the current study wore full “bunker gear” prohibiting the use of skin-based markers requiring a marker-less approach and performed a multi-planar lifting task. Although more the task represented a more accurate representation of actual task performance, it was also associated methodological challenges as previously discussed.

When considering measurement properties of this approach, the standard error of measurement (SEM) and minimal detectable difference (MDC) of relative hip vertical displacement and knee angle is considerably lower than trunk angle. Absolute reliability for tracking knee and trunk angle suggest that when observing movement from a frontal camera position, one could be 95% confident that a change of at least 10.5° and 20.8° respectively, between two measures would reflect a true change in score. Similar findings regarding absolute reliability were identified for tracking knee and trunk from the sagittal camera angle. When considering hip vertical displacement, more than a 5% change in relative hip movement will be needed to reflect a true change in hip displacement from the frontal camera position and 13% change from the sagittal camera position. As previously discussed, these findings suggest that measuring knee angles using Dartfish is associated with higher reliability than trunk postures, although the accuracy of these measures requires further investigation.

Limitations and strengths

Our study results are proof-of-concept that using Dartfish to analyze knee and trunk postures from video images provides a feasible, reliable approach to identify multi-planar, lower extremity postures associated with a fire-fighting lift task however several important limitations were observed. The most critical limitation was identified when using the Dartfish angle tracking to measure trunk and knee angles obtained from sagittal camera video. Because participants' rotated perpendicular to the frontal camera plane, the task perspective was also in a frontal plane when viewed from the sagittal camera. Consequently, several methodological issues when determining trunk and knee angles were identified. For example, determining valid representation of body segments necessary to identify relative angles was challenging particularly as landmarks identified on fire-fighting equipment became occluded during task performance by moving body segments and equipment used to perform the task (i.e., high-rise pack). Although angle tracking provides interesting information about the variability in the movement, our results from conducting single frame analysis suggest that measuring maximum and minimum angles from single frames of reference as in previous research [21,22], is a more feasible approach. Future research to validate this approach is needed with a particular focus on multi-planar movements such as those that involved in lifting, as attempted in the current study.

In addition to aforementioned methodological challenges, a primary limitation of this proof-of-concept study was the small sample. Utilizing a small sample was intentional as we intended to explore the feasibility of using Dartfish to measure kinematics during a multi-planar movement with few process controls as would be required in applied ergonomic contexts. We anticipated limitations analyzing multi-planar movements with a 2-dimensional approach; consequently we introduced additional Dartfish analytics such as positional co-ordinate tracking to identify task-based postures. A small sample was selected to determine feasibility of the selected approaches with the intention of up scaling to a larger sample upon confirmation.

The application of a postural assessment method in an applied occupational context is the primary strength of the current study. Our findings suggest that analysis of trunk and knee postures during a complex, multi-planar lift task can be obtained using marker-less, video-based inputs obtained from a field-based occupational context. Based on the measurement properties associated with the three measurement approaches (i.e., angle tracking, anatomical positional tracking, single frame analysis), study results suggest further investigation using anatomical positional tracking to analyze similar tasks in a larger sample is warranted.

Future directions

Tracking anatomical positional co-ordinates of the hip and converting the outputs to an anatomical reference provided useful information about task performance strategies. Further research is planned to investigate validating this analytical approach to angle measurements and compare to task ergonomics in a larger sample of fire-fighters performing the same task. If this approach can be validated, future research is anticipated where analyzing task performance strategies before and after implementation of interventions designed to mitigate exposure to risk factors associated with musculoskeletal disorders (i.e., awkward postures) can be conducted. Developing a simplified analytical approach that facilitates reliable, valid analyses of fire-fighter postures from video-based inputs, has implications for empowering ergonomists and fire-fighters to evaluate impacts of interventions designed to improve the health and safety of the fire service.

Conclusion

The primary objective of this study was to determine the feasibility of measuring trunk and knee postures during a fire-fighting lift task using a marker-less approach with Dartfish movement analysis software. Although trunk and knee postures were characterized, reliability of trunk measures was low. Recommendations include consideration and validation of positional-tracking versus angle measurements when using 2D analysis to identify characteristics associated with work postures in applied contexts. Although the study found that Dartfish was feasible to assess lower extremity postures during a multi-planar lift task, further research is required to validate this approach and to apply to a larger sample. If validated in a larger sample, the results from this research have implications for use in ergonomic contexts to evaluate impacts of interventions designed to mitigate risk factors associated with musculoskeletal disorders.

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