IDENTIFY AND MODEL FIREFIGHTER LOWER EXTREMITY POSTURES

MOVEMENT ANALYSIS OCCUPATIONALLY VALID EVALUATION USING VIDEO SOFTWARE IN THE CONTEXT OF FIREFIGHTERS HIGH-RISE LIFTING TASK

BY

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CONTRIBUTIONS:

The current thesis has been formatted according to the requirements of the Journal to which they will be submitted. Even though the paper is coauthored by more than one person, Ze Lu was contributed to all aspects of study which include, designing the protocol, analyses and writing of the manuscript.

JC MacDermid was the PI on the grant that funded the cohort study from which this data was collected, contributed to study design and analysis of the manuscripts and helped revise the manuscripts. Kathryn Sinden was a co-I on the grant that funded the cohort study from which this data was collected, contributed to study design and analysis of the manuscripts and helped revise the manuscripts. Vickie Galea helped provided guidance on analysis and revision of manuscripts.

ABSTRACT

Firefighting is associated with high rates of musculoskeletal (MSK) injury. Overexertion is the most common source of MSK injury among firefighters. Evaluation of how tasks are performed can identify injury risks. Use of video-based software can help quantify firefighter tasks, but requires accuracy despite complex movement and equipment/clothing interfering with line of sight. Therefore, the purpose of this study was to describe hip and knee joint motion performance while lifting a high-rise pack (HRP) from floor to shoulder and to determine the relationship between hip joint displacement and isolated hip and knee joint angles.

All the tasks were captured and measured as part of a larger FIREWELL study involving a total of 48 active firefighters. The kinematic information was extracted with the Dartfish© program using angle tracking and positional coordinates methods.

The results of the current study indicate that lifting a high-rise pack involves a knee arc of motion of 84 ^{0} (SD = 29^0) for the left side and 96 ^{0} (SD = 33^0) for the right side. Displacement of the hip joint may be useful to estimate knee motion where angle measurements cannot be reliably obtained. The need to normalize displacement by height remains unclear.

Future studies on video capture methods should focus on the a) reliability, b), ability to potential measure for change, c) predictive value of different movement indicators in task retraining videos.

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CHAPTER 1: INTRODUCTION

1. Firefighting tasks

Firefighting is considered one of the most hazardous careers associated with musculoskeletal injuries, requiring high physical exertion and rapid emergency response (Kumar, 2001; McGill, Frost, Andersen, Crosby, & Gardiner, 2013; Huiju Park et al., 2015; Rhea, Alvar, & Gray, 2004; Vieira & Kumar, 2004). Based on previous studies, nearly one- third of the more than 1 million US firefighters will experience a work-related injury, resulting in costs of $7.8 billion per year (Kumar, 2001; H Park et al., 2015; Vieira & Kumar, 2004). Although an ambiguous relationship exists between job characteristics and injury risk (Punakallio, Lusa, & Luukkonen, 2003), overexertion resulting in strain, sprain, and muscular pain has been reported as the leading cause (55.3%) of injury during fire-fighting, as well as the major cause (59.0%) of all the non-firefighting injuries (McGill et al., 2013; Rhea et al., 2004). During fire-fighting duties, frequent movements such as heavy lifting, holding, pulling, pushing and carrying of physical loads have demonstrated associations with overexertion leading to an increasing injury rate (Huiju Park et al., 2015; K. Park, Hur, Rosengren, Horn, & Hsiao-Wecksler, 2010; Punakallio et al., 2003). In addition, falls, slips and jumps also contribute substantively (22.5%) to the fire-fighting injuries (Hoogendoorn et al., 2015; Sobeih, Davis, Succop, Jetter, & Bhattacharya, 2006). With the goal of elucidating the nature and strength of the relationships between overexertion and fire-fighting injury, all the basic elements of movements, (such as angles, duration, time and distance) during fire-fighting activities should be recorded and analyzed carefully. Besides the movement itself, kinematic variables can also help researchers to quantify the work injury risk in future studies. For example, utilizing the Ovako Working

Posture Analysis System (OWAS) work injury risk assessment system to evaluate the dangerous level of a series of working postures, specific kinematic variables, such as joint angles, should be measured precisely (Maykut, Taylor-Haas, Paterno, DiCesare, & Ford, 2015; Vieira & Kumar, 2004). Understanding basic kinematic information, including angles, displacement and time duration enables us to uniformly document the movement pattern of a fire-fighting task, identify inappropriate working postures (awkward positions), and potentially help firefighters to decrease the risk of work related injury (Butler, Plisky, Southers, Scoma, & Kiesel, 2010; McLean et al., 2005). Therefore, evaluating movements during performance of firefighting tasks from a kinematic perspective may provide a useful measurement foundation on which to build future examinations of work demands and injury prevention.

2. Ecological validity of kinematic research in firefighting

Previous studies (McGill et al., 2013; Rhea et al., 2004) have measured firefighters' fitness, and movement during fire-fighting task performance. However, the nature of this laboratory-based research restricts the application to the real-world occupational environment. The applied context plays a significant role in the study of firefighters, as it could influence how the task would be performed. For instance, firefighters are required to wear personal protective equipment (PPE) known as 'bunker gear' during occupational tasks in the extreme environments they may encounter. Firefighter PPE includes coat, pants, boots, and the self-contained breathing apparatus (SCBA), which together mitigate the firefighters' risk of burns, suffocation, and trauma (Huiju Park et al., 2015; K. Park et al., 2010). The combined weight of the bunker gear exceeds 20 kg. The additional physical burden associated with this PPE could impede a firefighter's movements, and increase individual risk of experiencing musculoskeletal injuries during task performance (K. Park et al., 2010; Punakallio et al., 2003; Sobeih et al., 2006). More specifically, a recent study (Huiju Park et al., 2015) suggested that one of the PPE components, boots, could restrict lower extremity movement of firefighters by decreasing the range-of-motion of the ankle and forefoot, thereby increasing the risk of experiencing foot and ankle injuries. Within existing working injury assessment tools, such as OWAS and Rapid Entire Body Assessment (REBA), the risk of injury would increase to a higher danger level when the work load exceeds 20kg (Hoogendoorn et al., 2015; Vieira & Kumar, 2004). Based on the findings from previous studies (Huiju Park et al., 2015; Sobeih et al., 2006), it is important to take PPE into consideration when measuring kinematic features associated with firefighter task performance and investigating the link between job features and injury risk, in order to support ecological validity in firefighters-related ergonomic research.

3. Motion analysis systems

Amongst all the measurements in the biomechanics area, three-dimensional (3D) movement analysis systems, have been commonly considered as the gold standard of measurement in the field of ergonomics (Maykut et al., 2015; McLean et al., 2005). With the integration of the skin-based markers, highly sensitive cameras, non-reflective data collection environments and force plates, most spatial and temporal kinematic information can be recorded and analyzed precisely (Butler et al., 2010; Eltoukhy, Asfour, Thompson,

& Latta, 2012; Maykut et al., 2015; Wang, Leow, & Leong, 2008). However, utilizing a 3D system to assess firefighters' movements in the occupational context encounters huge barriers, such as the substantial equipment expenditure, heavy reliance on professional experience, and challenges in placement of the skin-based markers(Butler et al., 2010). All these strict requirements make the application of 3D motion capture systems contraindicated within occupational fire-fighting contexts.

In order to understand work-related musculoskeletal injuries and disorders in depth, and develop a superior injury prevention system for firefighters, improved posture assessment which enables experts to obtain accurate kinematic data during firefighters tasks, such as lifting and carrying, is becoming more and more important (Kumar, 2001; Vieira & Kumar, 2004). For example, portable video analysis systems enable researchers to evaluate the level of injury risk without the restriction of a strict laboratory setting. OWAS and RULA could be used directly based on a static photograph or dynamic video.

Instead of capturing three-dimensional motions, other analysis systems based on the two-dimensional analytical resources such as video file input, seem to be an effective solution (Borel, Schneider, & Newman, 2011; Gregory, Narula, Howarth, Russell, & Callaghan, 2008; Khadilkar et al., 2014; Mahmoud, Othman, Abdelrasoul, Stergiou, & Katz, 2015; Melton, Mullineaux, Mattacola, Mair, & Uhl, 2011). Without the restriction of a laboratory environment, video data can be collected across diverse contexts, which facilitates the analysis of firefighters' occupational tasks. Many previous studies have been designed and conducted under a laboratory setting by incorporating widely accepted methods coming from 3D motion analysis. One of the novel approaches is utilizing the skin-based marker points to improve the precision of data analysis (Allen, James, & Snodgrass, 2012; Eltoukhy et al., 2012; Holden, Boreham, Doherty, Wang, & Delahunt, 2015; Maykut et al., 2015; Miller & Callister, 2009; B. S. T. Norris & Olson, 2011) using a 2D system. However, application of marker points is challenging in this context because firefighters are asked to wear the whole set of PPE during the performance of applied task.

Thus, Dartfish movement analysis software (Lausanne, Switzerland) could be applied for this study, as it is not dependent on skin-based markers. Dartfish, a two-dimensional, video-based motion analysis software system, has been widely used in the area of athletics for providing task-based feedback (Dempsey & Mathiassen, 2006) with abundant details, such as angles, displacement and time elapsed data, thereby helping athletes improve their competitive performance (Parsons & Alexander, 2012). By introducing Dartfish into kinematic research, lower extremity (B. S. T. Norris & Olson, 2011) postures can be assessed with acceptable reliability during the completion of some elemental movements, such as lifting (Allen et al., 2012), and jumping (Holden et al., 2015; Miller & Callister, 2009; Parsons & Alexander, 2012). Regarding the validity, previous studies compared Dartfish with 3-D motion capture system as the gold standard of evaluating kinematic variables, and found a moderate (Rosnow & Rosenthal, 1989; Wuensch, 2015) level of concurrent validity for analyzing lower extremity postures using video captured from both frontal and sagittal frames (Eltoukhy et al., 2012; Maykut et al., 2015). Within the Dartfish software, kinematic information including angles, and distances are recorded by recognizing and tracking the mark points placed on the given positions (anatomical location). For example, the knee joint angle can be evaluated by placing a mark point on the lateral femoral epicondyle as the vertex then connecting a line to this point from the greater trochanter and a second line from the lateral malleolus using the angle tracking feature in Dartfish. Besides this angle tracking function, Dartfish also provides other analysis instruments through its ‘analyzer’ function. Rather than focusing on the angle, tracking x, y positional coordinates to record body segment paths has been developed in recent years to maintain the reliability of the measurement in applied design (Eltoukhy et al., 2012).

4. Thesis objectives

In the best interest of measuring the complex occupational tasks for firefighters using Dartfish motion analysis software, the objectives of this thesis were:

1. To critically appraise the methodological quality of studies, compare the psychometric properties reported, and synthesize the available literature on the measurement properties of Dartfish software.
2. To identify and illustrate the hip and knee postures during firefighters’ lifting tasks within the applied context and determine the relationship between a hip joint displacement indicator (unadjusted or more normalized to height) and isolated hip and knee joint angles; and the extent to which height and weight contribute to hip joint displacement during the high-rise pack lift.

CHAPTER 2: STUDY ONE

METHODOLOGICAL QUALITY OF STUDIES ON THE MEASUREMENT PROPERTIES OF A TWO-DIMENSIONAL MOVEMENT ANALYSIS SYSTEM: A SYSTEMATIC REVIEW

1. Rationale

Three-dimensional (3D) measurement is considered the gold standard to assess movement in the field of biomechanics (Dingenen et al., 2015; Dingenen, Malfait, Vanrenterghem, Verschueren, & Staes, 2014; McLean et al., 2005). Spatial and temporal kinematic information can now be precisely recorded and analyzed with the integration of skin-based markers, high sensitivity cameras, non-reflective data collection environments and force plates, (Butler, Plisky, Southers, Scoma, & Kiesel, 2010; Eltoukhy, Asfour, Thompson, & Latta, 2012; Maykut, Taylor-Haas, Paterno, DiCesare, & Ford, 2015). However, the barriers to using 3D measurement include substantial equipment costs, the need for operators with technical experience, and the requirements of a dedicated laboratory setting: this has led to the development and application of several supplementary movement measurement systems in recent years (Piriyaprasarth & Morris, 2007). Video-based movement analysis, or two-dimensional (2D) measurement, is an alternative system using an intelligent computer program to capture and analyze movements without the limitations of a strict laboratory setting and tedious associated procedures (Khadilkar et al., 2014; Sinden & MacDermid, 2016). Dartfish (Lausanne, Switzerland) is one of the 2D movement analysis systems applicable for this form of measurement.

Dartfish is a two-dimensional, video-based motion analysis software system that has been widely used in the area of athletics for providing task-based feedback (Dempsey & Mathiassen, 2006). The high level of detail including angles, displacement and time elapsed is assumed to help athletes improve their competitive performance (Parsons & Alexander, 2012). Within the Dartfish software, kinematic information can be captured and tracked by different methods, using 1) the automatic marker function (Melton, Mullineaux, Mattacola, Mair, & Uhl, 2011), and 2) a distance calibration tool built by the developers of the Dartfish (J. A. Paul & Douwes, 1993). However, in order to use this software for research purposes, it is important to evaluate the psychometric properties. Further, establishing the validity of 2D motion analysis will enable researchers to apply it on different populations and on various motion tasks.

Therefore, a need exists to understand what is known about the reliability and validity of Dartfish. Moreover, in order to examine the extent to which the traditional 3D motion analysis system could be replaced by Dartfish, reproducibility and systematic measurement error parameters must be considered (Borel, Schneider, & Newman, 2011; Gregory, Narula, Howarth, Russell, & Callaghan, 2008).

The purpose of this systematic review was to critically appraise the methodological quality of studies, compare the psychometric properties reported, and synthesize the available literature on the measurement properties of Dartfish software.

2. Method

Search

The primary author [ZL] conducted a systematic search in five electronic databases, PsychInfo, Embase, Medline@ Ovid, CINAHL and Google Scholar search engine (1999 to May 2016). To ensure a comprehensive search, the search strategy included the following keywords: movement analysis, two dimensional, and psychometric properties. Derivations of keywords were also been used in the search (Flow chart).

Selection of Studies

The authors [ZL, JM] screened all titles and abstracts and full texts of potentially relevant studies were retrieved (Appendix 1). Studies which obviously stated the use of a different software used or uninteresting tasks, such as surgical skills, were also considered irrelevant. The retrieved studies were then assessed for eligibility by the same authors independently, using the eligibility criteria which was formulated based on the agreement after the discussion between two authors. The specific eligibility criteria were as follow:

Inclusion criteria:

1. Analysis of movement must use Dartfish software
2. Purpose of the study includes reliability or validity or agreement of the measurements
3. Studies published in English

Exclusion criteria:

1. Interested factors were not included: angle or distance
2. Studies conducted on animals, cadavers or using mechanical models

3. Data Extraction

The data extracted were as follow: author, publication year, sample demographic, interesting variables, camera position, and measurement properties. Relevant statistical results and movements were also extracted. Details were listed in result section.

4. Quality Appraisal

The quality of the studies was assessed using the critical appraisal of study design for psychometric articles evaluation form (MacDermid et al., 2008) (Appendix 2). Key items of the quality checklist are scope of measurement properties, appropriate inclusion/exclusion criteria, specific descriptions of the measure, and appropriate analyses for each specific hypothesis or question. For example, the descriptions of measurements should include the camera positions. A total quality score was calculated for each study using the formula: sum of scores for each item divided by the numbers of items and multiplied by 100% (MacDermid et al., 2008). Both reviewers appraised the full test independently. The quality of the studies were also categorized as poor (0% - 30%), fair (31% - 50%), good (51% - 70%), very good (71% - 90%), and excellent (>90%) (Figure 1).

The measurement properties of Dartfish were classified according to traditional benchmarks. . The level of reliability when reported as intra-class correlation coefficient (ICC) was categorized as $ICC < 0.40$ indicated poor, $0.40 \leq ICC < 0.75$ means fair to good and $ICC \geq 0.75$ indicated excellent reliability (Bunce, 2009). For construct validity outcomes, where Pearson or Spearman correlation coefficients or R-squared value was used to relate different measures, the strength of correlation coefficient was classified as: 0.00-0.19 for ‘very weak’, 0.20-0.39 for ‘weak’, 0.40-0.59 for ‘moderate’, 0.60-0.79 for ‘strong’, 0.80-1.00 for ‘very strong’ (Evans et al.1996).

5. Results

Search

A total of 754 studies were identified from the search in the databases [Embase (n = 509), Medline (n = 205), PsyInfo (n = 22), CINAHL(n=0) and Google Scholar (n = 18)], of which 101 studies were considered relevant. All 101 studies were retrieved and assessed for eligibility, and a total of 22 studies were included in this review (Figure 1). Reasons for exclusion at the abstract review stage included: purpose of study does not include measurement properties such as reliability or validity and range of movement has not been analyzed.

Study Characteristics

Participant demographics and study methodological design of the included studies are described in Table 1. Fifteen studies were reliability studies (Dingenen et al., 2014; Fourchet, Materne, Horobeanu, Hudacek, & Buchheit, 2013; Gregory et al., 2008; Khadilkar et al., 2014; Mahmoud, Othman, Abdelrasoul, Stergiou, & Katz, 2015; Maykut et al., 2015; Melton et al., 2011; Mier, 2011; Miller & Callister, 2009; B. S. T. Norris & Olson, 2011; J. C. Paul et al., 2015; Redler et al., 2016; Sinden & MacDermid, 2016; Souza et al., 2015; Stensrud, Myklebust, Kristianslund, Bahr, & Krosshaug, 2011) and 10 reported the validity of Dartfish. Seven studies reported both reliability and validity. In addition, three studies (Borel et al., 2011; Gregory et al., 2008; Mahmoud et al., 2015) reported agreement. Seven studies identified specific clinical measurement hypotheses (Khadilkar et al., 2014; Maykut et al., 2015; Mier, 2011; Nagano, Sakagami, Ida, Akai, & Fukubayashi, 2008; B. S. T. Norris & Olson, 2011; J. C. Paul et al., 2015; Redler et al., 2016). Most studies provided a detailed description of study design and conducted specific statistical analysis to obtain estimates of the measurement property. The reported statistical results of all studies are summarized in Table 2.

Methodological Quality of Studies

The methodological quality evaluation of the reviewed studies is tabulated in Table 3. Quality score varied from individual studies, ranging from 32% to 92%. Amongst all studies, 56% of the papers (n = 13) reached or exceeded a score of 71%. Five studies were evaluated as fair quality (31%~50%) and no studies were rated as poor quality (0%~30%). Participants. Most studies used a convenience sampling strategy. Most of the studies recruited approximately 30 participants and the rationale of recruiting an appropriate sample size of participants was reported in only four studies (Fourchet et al., 2013; Nagano et al., 2008; Redler et al., 2016; Souza et al., 2015). Redler et al. (2016) recruited the largest sample size of 242 to establish the inter-rater reliability. Four studies recruited only females or males in order to eliminate potential group variance due to sex (Fourchet et al., 2013; Gregory et al., 2008; Nagano et al., 2008; B. S. T. Norris & Olson, 2011). Infants were recruited in a single study by Christensen, Castle, & Hussey (2015). One of the studies (Katayanagi et al., 2015) had participants nearly 60 years old for mean age. Two studies reported the range of age of their samples between 3 to 12 years (Mahmoud et al., 2015), and 1 to 12 years (Redler et al., 2016).

Data collection methods: Five of the articles considered the single-leg vertical drop jump (SLVDJ) as the movement of interest (Ayala, n.d.; Dingenen et al., 2014; Gregory et al., 2008; Miller & Callister, 2009; Redler et al., 2016; Stensrud et al., 2011). Two studies analyzed a lifting task (B. S. T. Norris & Olson, 2011; Sinden & MacDermid, 2016). Angle and distance were the major variables of interest amongst all studies. Two studies also included velocity and time in the data analysis (Borel et al., 2011; Melton et al., 2011). Four studies conducted the movement analysis by Dartfish through both the frontal and sagittal perspectives (Borel et al., 2011; Gregory et al., 2008; Khadilkar et al., 2014). However, the video analysis frame was not been mentioned in one study (Mier, 2011). In order to establish the validity or agreement between the Dartfish and other motion analysis system, the following secondary systems were used: 3D (Constand & Macdermid, 2013; Dingenen et al., 2014; Gregory et al., 2008; Maykut et al., 2015; McLean et al., 2005; Nagano et al., 2008), X-ray in Junya study (Katayanagi et al., 2015), goniometry (Mier, 2011; B. S. T. Norris & Olson, 2011), VERT device (Mahmoud et al., 2015), and Datapac (Melton et al., 2011).

Reliability: A total of 16 studies assessed reliability. Eleven studies had appropriate statistical testing (Score of 2 on Item 10 of quality tool). Out of these studies, five studies reported point-estimates with appropriate ancillary analysis, that is, were scored 2 on both Items 10 and 11 of the quality tool. In addition to traditional ICC, another point estimate reliability indicators used was the coefficient of variation was used (Fourchet et al., 2013).

Inconsistent test-retest reliability was established for measuring different body segment or video analysis frame (Khadilkar et al., 2014; Miller & Callister, 2009; B. S. Norris & Olson, 2011; Stensrud et al., 2011). For example, the test-retest reliability of applying Dartfish to measure knee joint angle through single-leg squat varied from fair to excellent strength left and right extremities (Stensrud et al., 2011). Several studies obtained a good to excellent rating for inter-rater reliability indicating no obvious variation between measurements applied by individual raters and the same person (Ayala, n.d.; Dingenen et al., 2014; Gregory et al., 2008; Khadilkar et al., 2014; Maykut et al., 2015; Mier, 2011; B. S. Norris & Olson, 2011; Redler et al., 2016; Sinden & MacDermid, 2016; Souza et al., 2015). Meanwhile, similar strength was found for intra-rater reliability (Ayala, n.d.; Dingenen et al., 2014; Khadilkar et al., 2014; Maykut et al., 2015; Mier, 2011; B. S. Norris & Olson, 2011; Sinden & MacDermid, 2016; Souza et al., 2015). In addition to the point estimate of reliability, confidence intervals (CI) and benchmarks were reported in most studies as ancillary statistical analysis. Without the statistical analysis of ICC, two studies reported mean difference (Christensen et al., 2015; McLean et al., 2005). In one study, a paired t-test was conducted to compare the visual estimation and Dartfish on measuring active cervical motion in rotation (Christensen et al., 2015). Both inter- and intra-rater reliability were reported using kappa coefficients, where a value of 1.00 indicates perfect agreement (Redler et al., 2016). The strength of reliability for measuring both firefighting high-rise lifting task (Sinden & MacDermid, 2016) and simple sit and reach movement (Mier, 2011) had similarly excellent level of reliability. With the consideration of different camera positions when using Dartfish, two studies revealed variability in the reliability when using the frontal and sagittal analysis frame (Khadilkar et al., 2014; Sinden & MacDermid, 2016).

Validity: Six studies reported the validity for motion analysis focusing on joint angle or distance (Ayala, n.d.; Dingenen et al., 2014; Gregory et al., 2008; Katayanagi et al., 2015; Mahmoud et al., 2015; Maykut et al., 2015). Criterion validity was indicated by concurrent validity between Dartfish and the secondary system, and was evaluated using correlation or regression coefficients (r and r2 respectively). Besides comparing the Dartfish with a 3D motion analysis system for tracking dynamic kinematic information, VERT and Datapac was also included in two different studies (Mahmoud et al., 2015; Melton et al., 2011). Fair to good quality was evaluated for these studies respectively. X-ray, and goniometric for static joint angle measuring was considered as the standard to evaluate the validity of Dartfish in two studies (Katayanagi et al., 2015; B. S. Norris & Olson, 2011). The Norris & Olson study (2011) was ranked as the first place (score: 92) of all studies through quality evaluation. Another motion measure strategy, visual estimation was used in one study (Christensen et al., 2015). However, only paired t-test has been reported. Although the majority of the studies reported good reliability (as indicated by a high value of ICC), the statistical outcomes for validity ranged between very weak to weak. For example, in the Dingenen et al. (2014) study, the reported ICC ranged from 0.79 to 0.99, but the Pearson correlation coefficient was 0.11 to 0.36; this was a similar finding in the Maykut et al. (2015) study. In studies that used 3D as the secondary system, r values ranged from 0.16 to 0.88 (Ayala, n.d.; Dingenen et al., 2014). When tracking the dynamic joint angle, the r values were rated as very weak. Meanwhile, the r value for tracking distance was rated strong to very strong (Ayala, n.d.). The strength of validity was rated strong to very strong for studies comparing Dartfish with static movement analysis software (Katayanagi et al., 2015; B. S. Norris & Olson, 2011). One study used regression analysis (Nagano et al., 2008) by including knee valgus angle during a continuous jump test from 2D and 3D, and the R-square of three different regression models (values approximately 0.40) were all statistically significant.

The Bland-Altman graphs measure the difference between different measurements when analyzing the same kinematic components and provide researchers with visual inspections of the distribution of retest errors across the spectrum of scores. The mean difference along with 95% Limits of Agreement (LoA) is used to o quantify the strength of the agreement (Bunce, 2009). Three studies reported the inter-device agreement by different indicators (Borel et al., 2011; Gregory et al., 2008; Melton et al., 2011). Cohen kappa coefficient has been reported for observational gait scale (0.78) and Dartfish gait assessment (0.81) on measuring the gait of normal walking (Borel et al., 2011). LoA was used to measure agreement of the velocity and angle of shoulder in one study (Melton et al., 2011). An difference has been found between Datapac (7°) and Dartfish (37°) in terms of the velocity. In one study the graph, was presented without the LoA, (Gregory et al., 2008).

Measurement Error: Six studies reported the standard of error measurement (SEM) and/or the minimal detectable change (MDC) as the indicator to quantify the measurement error (Khadilkar et al., 2014; Melton et al., 2011; Mier, 2011; J. C. Paul et al., 2015; Sinden & MacDermid, 2016; Souza et al., 2015). For tracking angle during a given movement, nearly 10° variation had been found in three studies (Khadilkar et al., 2014; J. C. Paul et al., 2015; Sinden & MacDermid, 2016). Meanwhile, other studies reported a small measurement error (1° - 3°).

6. Discussion

This systematic review determined that Dartfish software has been used to assess movement in a wide range of contexts, and that overall the methodological quality of studies was very good to excellent. This suggest that the Dartfish could be used as a reliable and valid measurement tool for assessing dynamic movements. The evidence identifies that measurement error varies across contexts; but with appropriate consideration of potential sources of error inherent in 2-dimensional motion analysis, such as camera setting, movement standardization and normalized kinematic information extraction procedures, reported results of the related study should be treated with confidence.

. Although good to excellent reliability was reported in some studies, the relatively small sample size or restricted age range of the participants, were common limitations of the included studies, which would influence the generalizability of the study results. Furthermore, the lack of appropriate sample size calculation was common in 16 studies. Acknowledging that excellent reliability does not necessarily indicate excellent sensitivity of the measurement tools. The coefficient of variation can be used to quantify the difference between different raters or methods (Fourchet et al., 2013). In addition to point estimate statistical analysis, CI, SEM and MDC was reported by most authors. This review established that a variety of statistics have been used to assess reliability of Dartfish scores. These have established parameters of group level reliability, agreement and absolute reliability that can be applied when making allowance for measurement error in different contexts where Dartfish has been used.

Despite favorable reliability, the validity has been questioned in three studies (Ayala, n.d.; Dingenen et al., 2014; Maykut et al., 2015). Perspective error was attributed as the reason for, tracking angle being unstable. Another factor that could have influenced studies findings was the nature of the study samples. Correlation coefficient can be affected by age, gender and other factors that might influence study measures. For example, only females were recruited in several studies (B. S. Norris & Olson, 2011)

Despite the known limitation of e perspective error existing in all 2D measurements of 3D motion, the current systematic review found Dartfish to be a reliable and valid motion analysis system to quantify the angle and distance during various movements. Moreover, based on Paul et al, (J. A. Paul & Douwes, 1993) several strategies can be used to minimize the magnitude of perspective error and be introduced during the study design phase. Dartfish produces similar results to X-ray and goniometry for quantifying static distance and angle. For measuring dynamic motions, Dartfish should be applied carefully for the multi-planar movements.(Paul & Douwes, 1993).

Studies often are unclear about terminology around agreement and reliability (Redler et al., 2016). Dartfish has been shown to provide reliable movement analysis system for various kinds of motions from simple sit and reach testing to more complex mechanical lifting task.

Limitations & Future Recommendations: Only studies published in English were included. The attempt to contact authors to obtain important details, which may not be mentioned in the original paper, was not been made. This review was also only limited to one movement analysis software, Dartfish; there are several other 2D movement analysis systems, such as Datapec. Future studies reviewing studies to include other systems will allow the comparison amongst different 2D movement analysis systems. The quality appraisal tool used in this review focused primarily on methodological design of studies, and this tool currently lacks specific criteria of good statistical outcomes. Criteria which evaluate the quality of statistical outcomes is recommended to be used in conjunction. Thus, the authors recommend that future measurement studies should design and report their studies using such a quality appraisal tool to ensure high-quality studies and reporting. The use of quality appraisal tools also ensures that details of follow up information will be recorded carefully and treated with suitable analyses. Lastly, for future studies on multi-planar movement analysis, efforts should be made to minimize the magnitude of perspective error. For example, add an overlook position camera and adjustment of the rotational angle could be an effective solution

7. Conclusion

Available evidence suggests that Dartfish may be a reliable and valid measurement for quantifying kinematic information on various movements. For future study, it is necessary to report study finding according to the high quality appraisal of methodological design and statistical outcome. Particular effort should be taken on quantifying the dynamic or multi-planar movement using Dartfish.

8. References List

(OHSCO), O. H. and S. C. of O. (2007). Musculoskeletal Disorder (MSD) Prevention Guideline for Ontario.

Allen, J. L., James, C., & Snodgrass, S. J. (2012). The effect of load on biomechanics during an overhead lift in the WorkHab Functional Capacity Evaluation. *Work (Reading, Mass.)*, *43*(4), 487–96. http://doi.org/10.3233/WOR-2012-1386

Borel, S., Schneider, P., & Newman, C. J. (2011). Video analysis software increases the interrater reliability of video gait assessments in children with cerebral palsy. *Gait & Posture*, *33*(4), 727–9. http://doi.org/10.1016/j.gaitpost.2011.02.012

Butler, R. J., Plisky, P. J., Southers, C., Scoma, C., & Kiesel, K. B. (2010). Biomechanical analysis of the different classifications of the Functional Movement Screen deep squat test. *Sports Biomechanics*, *9*(4), 270–279. http://doi.org/10.1080/14763141.2010.539623

Dempsey, P. G., & Mathiassen, S. E. (2006). On the evolution of task-based analysis of manual materials handling, and its applicability in contemporary ergonomics. *Applied Ergonomics*, *37*(1 SPEC. ISS.), 33–43. http://doi.org/10.1016/j.apergo.2004.11.004

Eltoukhy, M., Asfour, S., Thompson, C., & Latta, L. (2012). Evaluation of the Performance of Digital Video Analysis of Human Motion: Dartfish Tracking System. *International Journal of …*, *3*(3), 1–6. Retrieved from http://www.ijser.org/researchpaper/Evaluation_of_the_Performance_of_Digital_Video_Analysis_of_Human_Motion.pdf

Gregory, D. E., Narula, S., Howarth, S. J., Russell, C., & Callaghan, J. P. (2008). The effect of fatigue on trunk muscle activation patterns and spine postures during simulated firefighting tasks. *Ergonomics*, *51*(7), 1032–41. http://doi.org/10.1080/00140130701813178

Holden, S., Boreham, C., Doherty, C., Wang, D., & Delahunt, E. (2015). Clinical Biomechanics Clinical assessment of countermovement jump landing kinematics in early adolescence : Sex differences and normative values. *JCLB*, 6–11. http://doi.org/10.1016/j.clinbiomech.2015.03.008

Hoogendoorn, W. E., Poppel, M. N. M. Van, Bongers, P. M., Bart, W., Bongers, M., & Hoogendoorn, E. (2015). Finnish Institute of Occupational Health Danish National Research Centre for the Working Environment Norwegian National Institute of Occupational Health.

Katayanagi, J., Iida, T., Oyama, Y., Ato, A., Mine, K., Toumura, T., & Ozeki, S. (2015). Sagittal plane alignment evaluation during walking in adult spinal deformity : gait analysis using DARTFISH. *Scoliosis, 10*(Suppl 1), P21. http://doi.org/10.1186/1748-7161-10-S1-P21

Khadilkar, L., MacDermid, J. C., Sinden, K. E., Jenkyn, T. R., Birmingham, T. B., & Athwal, G. S. (2014). An analysis of functional shoulder movements during task performance using Dartfish movement analysis software. *International Journal of Shoulder Surgery*, *8*(1), 1–9. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4049033/

Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics*, *44*(1), 17–47. http://doi.org/10.1080/00140130120716

List, M., Directory, D., Open, O. F., & Journals, A. (2010). RESEARCHES CONCERNING THE UTILIZATION OF THE KINEMATIC ANALYSIS MOVEMENT SOFTWARE IN 2D SYSTEM – DARTFISH © IN THE MALE TRIPLE JUMP EVENT TECHNIQUE MONITORING MIHAI Ilie , Faculty of Physical Education and Sport, University of Pitesti, ROMANIA, (2), 2008–2010.

Mahmoud, I., Othman, A. A. A., Abdelrasoul, E., Stergiou, P., & Katz, L. (2015). The reliability of a real time wearable sensing device to measure vertical jump. *Procedia Engineering*, *112*, 467–472. http://doi.org/10.1016/j.proeng.2015.07.226

Maykut, J. N., & Ford, K. R. (2015). Concurrent validity and reliability , *10*(2), 136–146.

Maykut, J. N., Taylor-Haas, J. A., Paterno, M. V, DiCesare, C. A., & Ford, K. R. (2015). Concurrent validity and reliability of 2d kinematic analysis of frontal plane motion during running. *International Journal of Sports Physical Therapy*, *10*(2), 136–46. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=4387721&tool=pmcentrez&rendertype=abstract

McGill, S., Frost, D., Andersen, J., Crosby, I., & Gardiner, D. (2013). Movement quality and links to measures of fitness in firefighters. *Work*, *45*, 357–366. http://doi.org/10.3233/WOR-121538

McGrail, D. M. (2007). *Firefighting Operations in High-Rise and Standpipe-Equipped Buildings*. PennWell Books. Retrieved from https://books.google.com/books?hl=en&lr=&id=esXQpgf7QbcC&pgis=1

McLean, S. G., Walker, K., Ford, K. R., Myer, G. D., Hewett, T. E., & van den Bogert, a J. (2005). Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *British Journal of Sports Medicine, 39*, 355–362. http://doi.org/10.1136/bjsm.2005.018598

Melton, C., Mullineaux, D. R., Mattacola, C. G., Mair, S. D., & Uhl, T. L. (2011). Reliability of video motion-analysis systems to measure amplitude and velocity of shoulder elevation. *Journal of Sport Rehabilitation*, *20*(4), 393–405. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/22012494

Miller, A., & Callister, R. (2009). Reliable lower limb musculoskeletal profiling using easily operated, portable equipment. *Physical Therapy in Sport*, *10*(1), 30–37. http://doi.org/10.1016/j.ptsp.2008.10.003

National Interagency Fire Centre. (1996). Wildland Fire Suppression Tactics Reference Guide. *National Wildfire Coordinationg Group*, 353. http://doi.org/2004-689-253/603

Norris, B. S., & Olson, S. L. (2011). Concurrent validity and reliability of two-dimensional video analysis of hip and knee joint motion during mechanical lifting. *Physiotherapy Theory and Practice*, *27*(7), 521–30. http://doi.org/10.3109/09593985.2010.533745

Norris, B. S. T., & Olson, S. L. (2011). Concurrent validity and reliability of two-dimensional video analysis of hip and knee joint motion during mechanical lifting. *Physiotherapy Theory and Practice*, *27*(7), 521–30. http://doi.org/10.3109/09593985.2010.533745

Park, H., Trejo, H., Miles, M., Bauer, A., Kim, S., & Stull, J. (2015). Impact of firefighter gear on lower body range of motion Huiju. *International Journal of Clothing Science and Technology*, *27*(2), 315–344.

Park, H., Trejo, H., Miles, M., Bauer, A., Kim, S., & Stull, J. (2015). Impact of firefighter gear on lower body range-of-motion. *International Journal of Clothing Science and Technology, 27*(2), 315–334.

Park, K., Hur, P., Rosengren, K. S., Horn, G. P., & Hsiao-Wecksler, E. T. (2010). Effect of load carriage on gait due to firefighting air bottle configuration. *Ergonomics*, *53*(7), 882–891. http://doi.org/10.1080/00140139.2010.489962

Parsons, J. L., & Alexander, M. J. L. (2012). Modifying spike jump landing biomechanics in female adolescent volleyball athletes using video and verbal feedback. *Journal of Strength and Conditioning Research*, *26*(4), 1076–84. http://doi.org/10.1519/JSC.0b013e31822e5876

Paul, J. A., & Douwes, M. (1993). Two-dimensional photographic posture recording and description: a validity study. *Applied Ergonomics*, *24*(2), 83–90. http://doi.org/10.1016/0003-6870(93)90079-O

Punakallio, A., Lusa, S., & Luukkonen, R. (2003). Protective Equipment Affects Balance Abilities Differently in Younger and Older Firefighters. *Aviation Space and Environmental Medicine*, *74*(11), 1151–1156.

Rhea, M. R., Alvar, B. A., & Gray, R. (2004). Physical fitness and job performance of firefighters. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *18*(2), 348–352. http://doi.org/10.1519/R-12812.1

Rosnow, R. L., & Rosenthal, R. (1989). Statistical procedures and the justification of knowledge in psychological science. *American Psychologist*, *44*(10), 1276–1284. http://doi.org/10.1037/0003-066X.44.10.1276

Samuel B. Green. (1991). How Many Subjects Does It Take To Do A Regression Analysis. *Multivariate Behavioral Research*, *26*(3), 499–510. http://doi.org/10.1207/s15327906mbr2603

Sinden, K. E., & MacDermid, J. C. (2016). 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. *Journal of Ergonomics*, *06*(01), 1–10. http://doi.org/10.4172/2165-7556.1000145

Sobeih, T. M., Davis, K. G., Succop, P. a., Jetter, W. a., & Bhattacharya, A. (2006). Postural Balance Changes in On-Duty Firefighters: Effect of Gear and Long Work Shifts. *Journal of Occupational and Environmental Medicine*, *48*(1), 68–75. http://doi.org/10.1097/01.jom.0000181756.38010.d2

Vieira, E. R., & Kumar, S. (2004). Working Postures: A Literature Review. *Journal of Occupational Rehabilitation*, *14*(2), 143–159. http://doi.org/10.1023/B:JOOR.0000018330.46029.05

Wang, R., Leow, W. K., & Leong, H. W. (2008). 3D-2D Spatiotemporal Registration for Sports Motion Analysis.

Wuensch, K. (2015). Cohen ' s Conventions for Small , Medium , and Large Effects, 25–26.

Figure 1. The systematic review evidence flowchart.

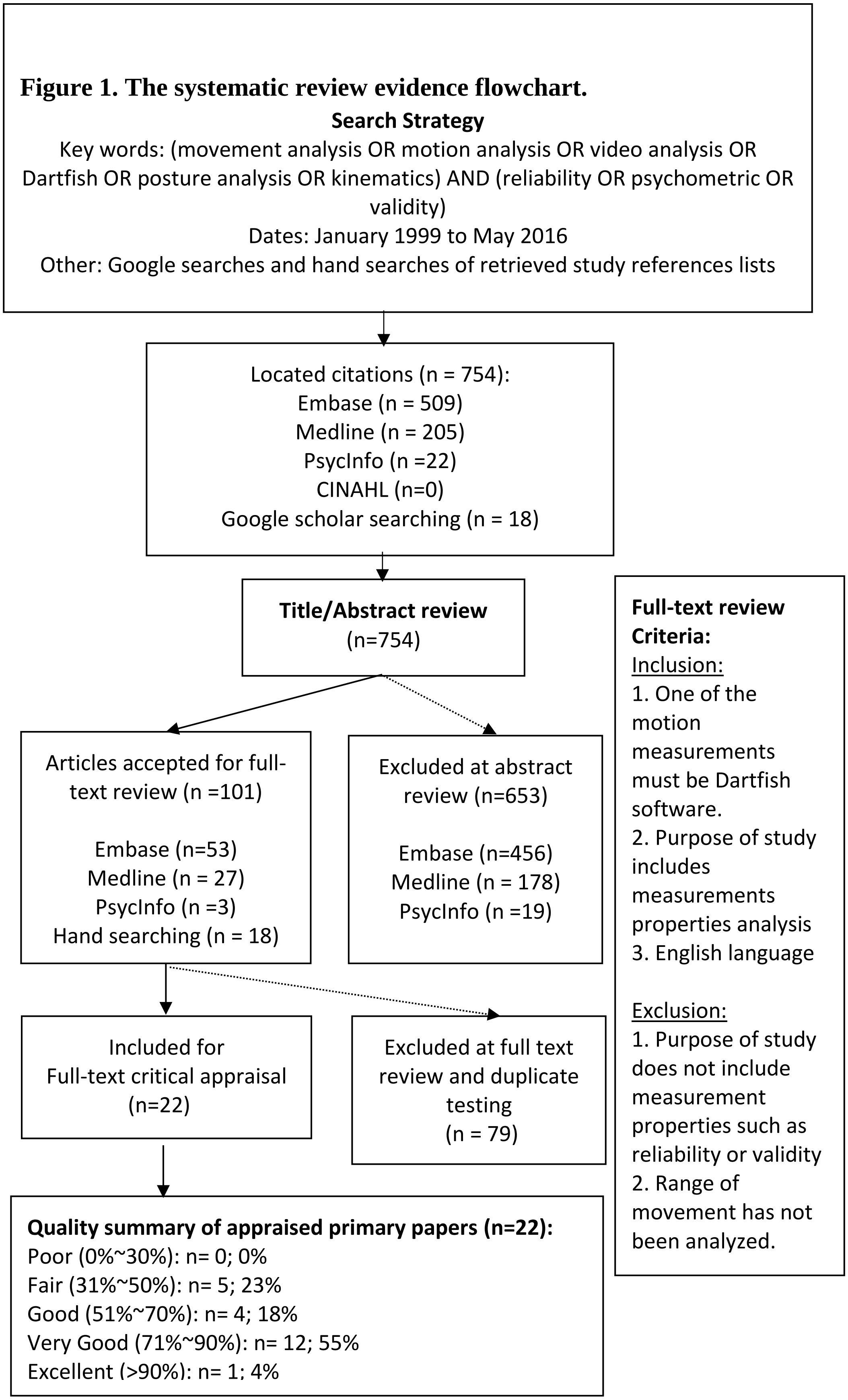


Table 1: Characteristics of included studies

Author, Publication Year	Population	Sample Size	Mean Age Years ± SD (range)	Interest variable	Camera Position	Measurement Property Assessed
Stensrud et al. 2011	Healthy female	184	22±4	Angle	Frontal	Test-retest reliability
Bart Dingenen et al. 2013	Healthy female	15	21.1±3.4	Angle	Frontal	Intra-rater reliability Concurrent validity
Junya et al. 2015	Spinal deformity patients	40	60.1	Angle	Sagittal	Concurrent validity
Andrew Miller et al. 2008	Health	24	23.7 (21.2–26.3)	Angle	Sagittal	Test-retest reliability
Beth S Norris et al. 2011	Healthy female	15	21~39	Angle	Sagittal	Reliability: Intra-rater Inter-rater Test-retest Concurrent validity
Jennifer N et al. 2015	Healthy runners	24	19.9±1.3	Angle	Frontal	Intra-rater reliability Concurrent validity
Constance M. Mier et al. 2011	Health	60	25.0±9.3 M 23.7±7.9 F	Angle	NA	Reliability: Intra-rater Test-retest
Gregory D. Myer et al. 2012	Healthy athletes	20	-	Angle, Distance	Frontal Sagittal	Inter-rater reliability Concurrent validity Agreement

Kathryn E Sinden et al. 2016	Firefighters	12	40.5±8.3	Angle, Distance	Frontal Sagittal	Intra-rater reliability SEM
Islam Mahmoud et al. 2015	Healthy children	38	(3 – 12)	Distance	Sagittal	Reliability Concurrent validity
S. Borel et al. 2011	Children with spastic cerebral palsy	12	8.9	Angle, Distance Time	Frontal Sagittal	Agreement
Justin C. Paul et al. 2015	Health	10	24.5±2.4 23~30	Angle Distance	Sagittal	Reliability Inter-trial Inter-session Inter-rater CMC: Coefficient of multiple correlation
Christopher Melton et al. 2011	Healthy group Should injury	21	27 ± 6 H 29 ± 9 S	Angle Velocity	Sagittal	Inter-rater reliability SEM Agreement
Constance M. Mier et al. 2013	Health	30	25.6 ± 7.6 M 22.4 ± 2.2 F	Angle	Sagittal	Reliability SEM
François Fourchet et al. 2012	Male athlete	10	15.3 ± 1.6	Angle	Sagittal Overlook	Reliability:Coefficient of Variation
Leenesh Khadilkar et al. 2014	Health	10	29 ± 5	Angle	Coronal Sagittal	Inter-rater Test-retest

Carla N. et al. 2013	Health	16	25.5 ± 2.0	Angle Distance	Frontal	Reliability Intra-rater Inter-rater Concurrent validity
Eric Christensen et al. 2015	Infants	12	-	Angle	Frontal Overlook	Pair t-test
S G McLean et al. 2005	Athlete	20	20.2±1.9 M 21.1 ± 3.0 F	Angle	Frontal	Concurrent validity
Y. NAGANO et al. 2008	Healthy female	28	21 ± 1	Angle	Frontal	Validity
Richard B. Souza et al. 2015	Health	256	42.3 ± 10.9 (17-80) M 41.9 ±9.7 (20-65) F	Angle	Back	Intra-rater reliability
Redler et al., 2016	Athlete participant Professional observers	267	14.5 (11~17)	Distance	Frontal	Reliability Intra-rater Inter-rater

Table 2. Summary of studies addressing psychometric properties of Dartfish

Author, Publication Year	Movement	Measurement Property	
		Design	Result
Stensrud et al. 2011	**SLS:** single-leg squat; **SLVDJ:** single-leg vertical drop jump; **VDJ:** two-leg vertical drop jump	Test-retest	SLS, right leg ICC=0.57 SLS, left leg ICC=0.84 SLVDJ, right leg ICC=0.58 SLVDJ, left leg ICC=0.70 VDJ ICC=0.89
Bart Dingenen et al. 2013	**LTM:** lateral trunk motion; **SLS Dom:** single leg squat dominant leg; **SLS N-Dom:** single leg squat non-dominant leg; **SLDVJ Dom:** single leg drop vertical jump dominant leg; **SLDVJ N- Dom:** single leg drop vertical jump non-dominant leg; **KV:** knee valgus **KVLTM:** sum of knee valgus and lateral trunk motion	Intra-rater	SLS Dom: ICC=0.98 Measure 1 ICC=0.99 Measure 2 SLS N-Dom: ICC=0.99 Measure 1 ICC=0.99 Measure 2 SLDVJ Dom: ICC=0.98 Measure 1 ICC=0.99 Measure 2 SLDVJ N- Dom ICC=0.99 Measure 1 ICC=0.99 Measure 2
Junya Katayanagi et al. 2015	**Walking** Angle between the horizontal and EG lines. Set markers at the External auditory pore and the Greater trochanter, and de fine	Pearson correlation Vs X-ray and sagittal vertical axis	DARTFISH vs SVA r=-0.642 DARTFISH vs X-ray r=0.742

	the straight line between them as the EG line.	(SVA)	
Andrew Miller et al. 2008	Step-up Single-leg vertical jump Single-leg drop jump Single-leg spring	Test-retest	Step-up ICC=0.75 Single-leg vertical jump ICC=0.68 Single-leg drop jump ICC=0.64 Side spring ICC=0.71
Beth S Norris et al. 2011	Mechanical lift task	Intra-rater Inter-rater Test-retest	**Intra-rater** Hip flexion ICC=0.99 Knee flexion ICC=0.98 **Inter-rater** Hip flexion A – B ICC=0.92 A – C ICC=0.91 B – C ICC=0.98 A – B – C ICC=0.94 Knee flexion A – B ICC=0.95 A – C ICC=0.98 B – C ICC=0.93 A – B – C ICC=0.96 **Test-retest** Hip flexion ICC=0.79 Knee flexion ICC=0.91
Jennifer N et al. 2015	Treadmill running **CPD:** Contralateral pelvic drop **HADD:** Peak hip adduction angle **KABD:** Peak knee abduction angle	Intra-rater	HDD left leg ICC= 0.963 right leg ICC=0.951 CPD left leg ICC=0.958 right leg ICC=0.966 KABD left leg ICC=0.955 right leg ICC=0.976
Constance M. et al. 2011	**SR test:** sit-and-reach **PSLR:** Passive Straight-Leg	Intra-rater Test-retest	**Intra-rater** ICC= 0.998

	Raise Test		**Test-retest** SR Men ICC=0.99 Women ICC=0.98 PSLR Men ICC=0.79 Women ICC=0.89	
Gregory D. Myer et al. 2012	**Drop vertical jump** **KAM:** high knee abduction moments Knee valgus motion	Inter-rater	ICC: 0.60~0.78	
Kathryn E Sinden et al. 2016	**Firefighting high-rise lifting task** **Three method:** **Angle tracking** Positional coordinates Single frame analysis Knee joint angles Trunk joint angles Relative hip movement	Intra-rater SEM MDC90	**Frontal frame** **Angle tracking** Knee ICC=0.85 SEM=4.5° MDC90=10.5° Trunk ICC=0.72 SEM=8.9° MDC90=20.8° **Positional coordinates** Relative Hip Movement ICC=0.84 SEM=2% MDC90=5% **Single frame analysis** Knee ICC=0.97 SEM=2.6° MDC90=6.1° Trunk ICC=0.97 SEM=2.5° MDC90=5.8°	**Sagittal frame** **Angle tracking** Knee ICC=0.93 SEM=3.5° MDC90=8.2° Trunk ICC=0.82 SEM=7.9° MDC90=18.4° **Positional coordinates** Relative Hip Movement ICC=0.81 SEM=6% MDC90=13% **Single frame analysis** Knee ICC=0.94 SEM=5.6° MDC90=13.1° Trunk ICC=0.78 SEM=1.4° MDC90=13.1°

Islam Mahmoud et al. 2015	**Vertical jump height**	Reliability Validity (VERT device vs Dartfish)	**Internal consistency** Cronbach's alpha=0.953 R2=0.908 **Concurrent validity** Pearson correlation= 0.923 R2=0.851
S. Borel et al. 2011	Gait Knee flexion angle Children with spastic cerebral palsy Standard software vs Dartfish Observational Gait Scale	Agreement	**Cohen kappa (95%CI)** Standard: 0.778 (0.477–1.079) Dartfish 0.809 (0.509–1.109)
Justin C. Paul et al. 2015	1) Alternating maximum right and left rotation; (2) left and right side bend; (3) forward bend; (4) rise to standing from seated position in a chair. (5) walked on a treadmill at a speed of 1.0 m/s.	Inter-trial Inter-session Inter-rater MDC:	**Bending in the coronal** Spine inclination angle ICC: 0.92-0.97 **Standing hip and knee angles during simple forward bending** Hip ICC: 0.959-0.962; knee ICC: 0.914-0.934 **Rotation** ICC: 0.717-0.846 **Treadmill gait** Knee ICC: 0.904-0.927 Stride length ICC: 0.894-0.970 **Rising from a seated Position** Hip and knee ICC: 0.884-0.933

Christopher Melton et al. 2011	**AE:** active elevation **AAE:** active assisted elevation Upper extremity: shoulder	Inter-rater Inter-rial SEM	**MDC** Angle:2°~12.6° Distance: 2.5~4.8 cm Angle ICC: 0.90 ~ 0.99 Velocity ICC:0.70 ~ 0.97 **SEM** Angle: 1° ~ 3° Velocity: 1°to 2°/s **Intra-trial reliability** Minimum velocity for Datapac ICC = 0.64 Dartfish ICC = 0.52			
Constance M. et al. 2013	**SR: Sit- and- reach test** Spine and pelvic flexibility described by Thoratic (T), Lumbar (L), Pelvic (P)	Internal consistency Test-retest Inter-rater Intra-rater SEM 95%CI	**Internal consistency** **ICC** T:0.99 (0.97–0.99); L:0.95 (0.91–0.98); P:0.99 (0.99–1.00). **SEM** T:1.65°; L: 1.53°; P: 1.28°.	**Test-retest reliability** **ICC** T: 0.96 (0.91–0.98); L: 0.84 (0.67–0.92); P: 0.97 (0.95–0.99). **SEM** T:3.2°; L: 2.8°; P: 2.5°	**Intra-rater reliability** **ICC** T: 0.95 (0.89–0.97); L: 0.87 (0.74–0.93); P: 0.97 (0.94–0.99). **SEM** T:3.0°; L: 3.1°; P: 2.5°.	**Inter-rater reliability** **ICC** T: 0.94 (0.89–0.97); L: 0.82 (0.66–0.91); P: 0.97 (0.94–0.99). **SEM** T:3.2°; L: 3.2°; P: 2.3°.
François et al. 2012	**Flexibility of eight lower limb**	Coefficient of	**Coefficient of Variation**		**ICC**	

	muscle groups Adductors; Hip Flexors; Hip Medial Rotators; Hip Lateral Rotators; Quadriceps; Hamstring; Gastrocnemius; Soleus.	Variation 95% CI Reliability	Quadriceps 8.3% (7.5~9.3) Hamstrings 3.3% (3.0~3.7) Adductors 7.2% (6.5~8.0) Gastrocnemius 5.7% (5.1~ 6.3) Soleus 4.5% (4.0~5.0) hip flexors 2.6% (2.3~2.9) Hip medial rotators 9.6% (8.6~10.8) Hip lateral rotators 12.4% (12.2~14.0)	Quadriceps 0.86 (0.82~0.89) Hamstrings 0.80 (0.74~0.85) Adductors 0.85 (0.81~0.89) Gastrocnemius 0.66 (0.57~0.63) Soleus 0.93 (0.90~0.95) hip flexors 0.51(0.39~0.61) Hip medial rotators 0.92 (0.89~0.94) Hip lateral rotators 0.91 (0.88~0.93)
Leenesh Khadilkar et al. 2014	**Five activity of daily living (ADL) tasks** Opening a tight jar, Pushing a heavy door, Changing an overhead bulb, Washing one's hair, and Washing one's back Shoulder arc of motion	Test-retest Inter-rater SEM	**Test-retest reliability** Coronal plane ICC: 0.74 ~ 0.94 Sagittal plane ICC: 0.45 ~ 0.94 **Inter-rater reliability** Coronal plane ICC: 0.98 ~1.00 SEM: 0.51° ~ 2.20° Sagittal plane ICC: 0.68 ~ 0.99 SEM: 0.39° ~ 8.69°	

Eric Christensen et al. 2015	Active cervical motion in rotation and lateral flexion VE: visual estimation VA: video analysis Combined results from 12 raters	Pair t-test	**Lateral flexion L** Mean diff=20.78° p=0.005 Rater1(n=9) Mean diff=23.68° p=0.016 Rater2(n=3) Mean diff=12.10° p=0.13 Mean diff=19.37° p=0.047	**Lateral flexion R** Mean diff=13.39° p=0.006 Rater1(n=9) Mean diff=11.40° p=0.052 Rater2(n=3)	**Rotation L** Mean diff=8.87° p=0.100 Rater1(n=9) Mean diff=4.74° p=0.353 Rater2(n=3) Mean diff=21.23° p=0.231	**Rotation R** Mean diff=16.06° p=0.005 Rater1(n=9) Mean diff=11.68° p=0.039 Rater2(n=3) Mean diff=29.20° p=0.079
McLean et al. 2005	**Side jump** **Side stepping** **Shuttle running**	Concurrent Validity	**R-square between3D and 2D-Cam** Side jump: 0.19 Side stepping: 0.27 Shuttle running: 0.16			
Y. NAGANO et al. 2008	**Continuous jump test**	Concurrent Validity	linear model R2 =0.34, P <0.01 quadratic model R2 =0.40, P =0.01 logarithmic model R2 =0.41, P<0.01 Y: 3D knee abduction X: 2D knee valgus			

Redler et al., 2016	**Drop vertical jump test** knee separation distance	Inter-rater Intra-rater	**Inter-rater reliability** $\kappa = 0.92$ (95% CI: 0.829 ~ 0.969, $p < 0.05$) **Intra-rater reliability** $\kappa = 0.55$ (95% CI:0.49 ~ 0.61, $p < 0.05$),		
Carla N. et al. 2013	**DVJ: drop vertical jump** Two methods were both 2D. **KASR:** knee to ankle separation ratio Knee/ankle **KSD:** knee separation distance Knee abduction angle	Intra-rater Inter-rater	**Knee abduction angle:** **Method 1** Dominant leg: ICC-intra=0.95* ICC-inter=0.82* Non-Dominant leg: ICC-intra=0.96* ICC-inter=0.86*	**Method 2** Dominant leg: ICC-intra=0.95* ICC-inter=0.93 Non-Dominant leg: ICC-intra=0.94* ICC-inter=0.84	**KASR:** ICC-intra=0.92* ICC-inter=0.88* **KSD:** ICC-intra=0.81* ICC-inter=0.93*
Richard B. Souza et.al 205	**Treadmill run.** The angle of the shoe sole relative to vertical for the initial frames and the peak deviation	Intra-rater SEM	ICC=0.994 SEM=1.2 degrees; **Within measures** Media whips ICC=0.960 lateral whips ICC=0.953		

Table 3: Quality of studies on the psychometric properties of Dartfish

Author, Publication Year	Item Evaluation Criteria*												Total (%)
	1	2	3	4	5	6	7	8	9	10	11	12	
Norris 2011	2	2	2	2	0	2	2	2	2	2	2	2	92
Mier 2013	2	2	2	2	0	2	2	2	2	2	1	2	88
Sinden 2016	2	2	1	2	0	2	2	2	2	2	2	2	88
Maykut 2015	2	2	2	2	0	NA	2	2	2	2	1	2	86
Redler 2016	2	2	2	1	2	NA	1	2	2	2	0	2	82
Mier 2011	2	2	1	2	0	2	2	1	2	2	1	2	79
Souza 2015	1	2	1	1	2	2	2	2	2	1	1	2	79
Y. Nagano 2008	2	2	2	1	2	NA	2	2	1	1	1	2	79
Dingenen 2013	2	2	0	1	0	NA	2	2	2	2	2	2	77

S G Mclean 2005	2	2	1	1	0	NA	2	2	2	2	1	2	77
Fourchet 2012	2	1	0	2	2	1	2	2	2	1	1	2	75
Khadilkar 2014	1	1	2	2	0	2	2	1	2	2	2	1	75
Miller 2008	2	2	1	1	0	2	1	2	1	1	2	2	71
Melton 2011	2	2	1	0	0	NA	2	2	1	1	2	2	68
Stensrud 2010	1	1	0	2	1	2	2	1	1	2	1	1	63
Figueroa 2013	2	2	2	1	0	2	1	1	2	1	0	1	63
Paul 2015	1	2	0	2	0	NA	1	1	0	2	2	1	55
S. Borel 2011	2	1	1	0	0	2	1	1	1	1	0	2	50
Christensen 2015	2	1	0	1	0	NA	2	2	1	1	0	2	50
Myer 2012	1	1	1	1	0	NA	2	0	1	1	1	1	42
Mahmoud 2015	1	1	0	1	0	NA	2	1	1	1	0	1	41
Junya Katayanagi 2015 poster	1	0	0	0	0	NA	2	1	1	1	0	1	32

Abbreviations: NA, not applicable to paper.

Evaluation criteria: 1. Thorough literature review to define the research question; 2. Specific inclusion/exclusion criteria; 3. Specific hypotheses; 4. Appropriate scope of clinical measurement properties; 5. Sample size; 6. Follow-up; 7. Specific descriptions of measures were provided; 8. Measurement procedures were standardized; 9. Data were related for each question or hypothesis; 10. Appropriate statistical tests; 11. Appropriate ancillary statistical tests; 12. Accurate conclusions and relevant clinical recommendations

Appendix 1: Critical Appraisal Of Study Quality For Psychometric Articles Reference

	Score	Descriptors
Study question		
1		Research question
Study design		
2		Setting and Participants
3		Hypotheses and types of reliability and validity
4		Scope of psychometric properties
5		Sample size
6		Recruitment and retention
Measurements		
7		Measurement procedures
8		Standardization
Analyses		
9		Relation to hypotheses
10		Appropriateness of statistical tests

11		Benchmarks and CIs
Recommendations		
12		Conclusions and clinical recommendations

Appendix 2: Critical Appraisal Of Study Quality For Psychometric Articles Interpretation Guide

To decide which score to provide for each item on your quality checklist, read the following descriptors. Pick the descriptor that sounds <u>*most*</u> *like the study you were evaluating with respect to a given item.*

		Descriptors
Study question		
Score		
1 background and research question	2	The authors: - performed a thorough literature review indicating what is currently known about the psychometric properties of the instruments or tests under study - presented a critical, and unbiased view of the current state of knowledge - indicated how the current research question evolves from a current knowledge base - Established a research question based on the above.
	1	All of these above criteria were not fulfilled, but a clear rationale was provided for the research question
	0	A foundation for the current research question was not clear or was not founded on previous literature
Study design		
2 settings and participants	2	Specific inclusion/exclusion criteria for the study were defined, the practice setting was described and appropriate demographic information was presented yielding a study group generalizable to a clinical situation.
	1	Some information on person and place is provided (NOT ALL). For example, age/sex/diagnosis and the name of the practice (clinic name) without additional information. Information on the type of patients is briefly defined, but it is insufficient to allow the reader to generalize the study to a specific population
	0	No information on type of clinical settings or study participants is provided.
3 hypothesis and types of reliability	2	Authors identified specific hypotheses which included the specific type of reliability (intra/inter-rater or test-retest) or validity (construct/ criterion/ content; longitudinal/concurrent; convergent/divergent) being tested. For validity, expected relationships or constructs were defined.
	1	Types of reliability and validity being tested were stated, but not clearly defined in terms of specific hypotheses.

and validity	0	Specific types of reliability or validity under evaluation were not clearly defined nor were specific hypotheses on reliability and validity stated. (“*The purpose of this study was to investigate the reliability and validity of…*” can be rated it is zero if no further detail on the types of reliability and validity or the nature of specific hypotheses is stated)
4 scope of psychometric properties	2	An appropriate scope of psychometric properties would be indicated by 1. A detailed focus on reliability that included multiple forms of reliability (at least two of – intra-rater, inter-rater, test-retest) where both relative and absolute reliability were addressed. (e.g. ICCs and SEM/MID) 2. A detailed focus on validity that included multiple forms of validity (content- judgmental; structured e.g. expert review/survey or qualitative interviews) or statistical (e.g. factor analyses), construct (known group differences; convergent/divergent associations), criterion (concurrent/predictive), responsiveness; predictive, evaluative or discriminative properties were established 3. Some aspects of both reliability and validity were examined concurrently using multiple approaches/analyses.
	1	Two psychometric properties were evaluated, however, the scope of both was superficial or narrow (e.g. point estimates used for one type of reliability and only a single unidimensional validity hypotheses tested)
	0	The scope of psychometric properties was very narrow as indicated by only one form of reliability or validity hypothesis estimated/tested.
5 sample size	2	Authors performed a sample size calculation and obtained their recruitment targets. Post-doc power analyses and/or confidence intervals confirm that the sample size was sufficient to define relatively precise estimates of reliability or validity.
	1	The authors provide a rationale for the number of subjects included in the study, but did not present specific sample size calculations or post-doc power analyses.
	0	Size of the sample was not rationalized or is clearly underpowered.
6 (recruitment retention)	2	90% or more of the patients enrolled for study were re-evaluated.
	1	More than 70% of the eligible patients were re-evaluated.
	0	Less than 70% of the patients eligible for study were re-evaluated
Measurements		
7 (measure procedures)	2	The authors provided or referenced a published manual/article that outlines specific procedures for administration, scoring (including scoring algorithms handling of missing data) and interpretation that included any necessary information about positioning/active participation of the client, any special equipment required, calibration of equipment if necessary, training required, cost, examiner procedures/actions. Text describes key details of procedures.
	1	Procedures are referenced without any details or a limited description of procedures is included within text.
	0	Minimal description of procedures without appropriate references

8 (standardize)	2	All of the measurement techniques, including administration and scoring of the measurements were performed in a standardized way. This would include calibration of any equipment; use of consistent measurement tools and scoring, a priori exclusion of any participants likely to give invalid results/unable to complete testing (no exclusion of after enrollment participants); use of standardized procedures
	1	No obvious sources of bias, but minimal attention or description to ascertain the extent to which the above standards were maintained.
	0	No description of the extent to which the above standards were maintained or an obvious source of bias in data collection methods
Analyses		
9 (relation to hypothesis)	2	Authors clearly defined which specific analyses were conducted for the stated specific hypotheses of the study. This may be accomplished through organization of the results under specific subheadings or by demarcating which analyses addressed specific psychometric properties. Data was presented for each hypothesis.
	1	Data was presented for each hypothesis, but authors did not clearly link analyses to hypotheses.
	0	Data was not presented for each hypothesis or psychometric property outlined in the purposes or methods
10 appropriate-ness of Stat Tests	2	Appropriate statistical tests were conducted: 1. Reliability (e.g. Relative=ICCs for quantitative, Kappa for nominal data); absolute (SEM)) 2. Clinical relevance – e.g. minimal detectable change, minimally important difference, number needed to treat 3. Validity a. Validity associations- e.g. Pearson correlations for normally distributed data, Spearman rank correlations for ordinal data; or other correlations if appropriate b. Validity tests of significant difference- e.g. an appropriate global test like analysis of variance was used where indicated, with post-hoc tests that adjusted for multiple testing 4. Responsiveness- e.g. standardized response means or effect sizes or other recognized responsiveness indices were used.
	1	Appropriate statistical tests were used in some instances but suboptimal choices were made in other analyses.
	0	Inappropriate use of statistical tests
11 benchmark CI	2	For key indicators like reliability coefficients indices at least 2 of the following were presented 1.appropriate confidence intervals, 2. Comparison to appropriate benchmarks or standards or 3. SEM. Correlation matrices for validity analysis may not require that each individual correlation be presented with its associated confidence intervals; however, however confidence intervals and benchmarks should be used according to standards for that type of analysis.
	1	Either confidence intervals or appropriate benchmarks were used-not both
	0	Inappropriate use of benchmarks or confidence intervals or neither included
Recommendations		

12	2	Authors made specific conclusions and clinical recommendations that were clearly related to specific hypotheses stated at the beginning of the study and supported by the data presented.
	1	Authors made conclusions and clinical recommendations that were general but basically supported by the study data; OR authors made conclusions and clinical recommendations for only some of the study hypotheses
	0	Authors made vague conclusions without any clinical recommendations; conclusions or recommendations were in contradiction to the actual data presented

CHAPTER 3: STUDY TWO

UTILIZING A DIGITAL VIDEO ANALYSIS APPROACH TO IDENTIFY AND MODEL FIREFIGHTER LOWER EXTREMITY POSTURES DURING A LIFT

1. Rationale

A reliable and ecologically valid system is needed to generate kinematic information to formulate prevention strategies for firefighting work-related injury. To ensure a solid foundation for future research, the kinematic information should be dynamic, demonstrating expected correlations and represent the major features of the body postures. Additionally, viewed from a clinical perspective, diverse body segments need to make a contribution together to perform the given firefighting task, such as lifting the high-rise pack, hose dragging and heavy carrying. Therefore, the firefighting lift task should be treated as an entire movement instead of hundreds of separate angles or distance in a discontinuous timeline. However, the isolated angles or displacement extracted by Dartfish were not connected with each other, which means the kinematic variables could not provide clinical researchers with enough information of interest.

Based on the previous studies (Eltoukhy et al., 2012; Katayanagi et al., 2015; Khadilkar et al., 2014; List, Directory, Open, & Journals, 2010), inconsistent reliability has been reported for utilizing the Dartfish movement analysis system to extract kinematic variables. For example, according to Norris et al (B. S. Norris & Olson, 2011)., during a lifting task, test-retest reliability were 0.79 and 0.91 for hip and knee flexion, respectively. A range of Pearson correlation coefficient values representing concurrent validity have also been reported, varying across the body segments tracked and analyzed. For instance, based on Maykut et al (Maykut et al., 2015), when tracking the hip flexion angles, the correlation was 0.539 (p=0.007) for the left extremity and 0.623 (p=0.001) for the right side (Maykut & Ford, 2015). Through the previous systematic review in chapter 2, various camera settings, limitation of 2D motion analysis system, and recognition mechanisms of the Dartfish would be major reasons causing mentioned inconsistency problems.

Another consideration is the potential limitations inherent in the Dartfish methods of analysis. Unlike the 3D system, such as Vicon and Qualysis, skin-based markers could not be attached for tracking body segments. By recognizing a designated group of pixels, the 'markers' function in Dartfish software tracks and records angles and distances. However, the image displayed on the screen consists of numerous pixels containing different colors. Therefore, the markers can fail to track the anatomical points and deviate to another unrelated location when the selected pixel is obstructed by other pixels representing a similar color on the spectrum. At least three virtual markers need to be placed for tracking the joint angle information. However, given the occurrence of these tracking errors, the software operators must apply manual corrections to address the tracking error. This is performed by pausing the video clip tracking immediately when the deviation is identified relocating the markers to their required positions and then re-activating the tracking function. Therefore, more markers require more manual corrections. Although the manual corrections can help reduce the error of measuring, this remediation strategy is time consuming and reliant on a skilled operator.

Instead of performing movements in a single plane, most firefighters' tasks occur as multi-planar motions in the occupational context (Allen et al., 2012; Miller & Callister, 2009): this is difficult to capture and measure in two dimensional video analysis. According to J.A Paul et.al (Paul & Douwes, 1993), the major systematic error of capturing the multi-planar motion using 2-D video analysis is perspective error. More specifically, this source of error has been found to be related to placement of the camera and motion capture frame towards the movement plane of interest. If the error exists in a study, following elements, which are named as determinate variables, could influence the magnitude of the perspective error: “the rotational angle, the distance between the camera and the body segment, the distance in the photographic plane between the optical axis and the body segment”. (Paul & Douwes, 1993) One of the variables, the rotational angle was defined as the angle between the postural angle plane and the photographic plane (Paul & Douwes, 1993). To reduce the rotational angle, the optical axis should be placed perpendicular to the postural angle plane. However, it is unrealistic to maintain this ideal viewpoint during the whole movement procedure, using a stabilized system for high-quality video capture such as a tripod-mounted camera

To address limitations associated with measuring kinematic angles using 2D, another function in Dartfish, ‘positional coordinates’ has been introduced since this method could limit the usage of markers. Instead of tracking the joint angles, positional coordinates could help researchers to minimize the perspective error by eliminating the rotational angle. However, it is difficult to obtain clinically meaningful information through reporting the x, y positional coordinates (distance) independently. To remedy the limitation and obtain clinical information, angle tracking and positional coordinates should be combined.

Therefore, in order to bridge the gap between clinical application and the experimental data, the current study applied two movement analysis methods including angle tracking and positional coordinates in Dartfish to identify and illustrate the hip and knee postures during a firefighter’s lifting task within the applied context. Furthermore, to interpret the kinematic information in a clinical perspective, the internal relationship between hip & knee angles and vertical hip displacement was investigated.

The primary objective was to describe hip and knee joint motion performance of firefighters while lifting a high-rise pack from floor to shoulder.

The secondary objectives were to determine the relationship between a hip joint displacement indicator (unadjusted or more normalized to height) and isolated hip and knee joint angles; and the extent to which height and weight contribute to hip joint displacement during the high-rise pack lift.

2. Methods

2.1 Design

This study used two methods (angle tracking, positional co-ordinate tracking) to extract the kinematic data of lower extremity motions during high-rise lifting task as a secondary analysis of existing video files from previous work by Sinden et al (Sinden & MacDermid, 2016), and applied multiple linear regression to model the internal relationship amongst variables.

2.2 Participants

Based on the given video files, firefighters (n=48) from a single fire service in Southwestern, Ontario was selected as the representative sample for this study. A purposeful sample of female firefighters (n=6) and a random sample of male firefighter participants (n=42) were recruited (see Table 1).

2.3 Procedures

Context

The current study represents a secondary analysis of existing video files from a previous study (Sinden & MacDermid, 2016). Demographic data including participant ID, height, weight and the codebook containing the order of video files were transferred using excel files.

Task: Lifting a High Rise Pack

Lifting the high-rise pack (HRP) was selected in the previous study (Sinden & MacDermid, 2016) as targeting a task that firefighters identify as important during fire-fighting missions and highly associated with injury rates. The HRP (19.5 kg) involves two lengths of firefighting hose (15 m each; 30 m total) including an attached nozzle and accessories (i.e., wrench, couplings and other equipment). The HRP was designed for quick response to structural fires (i.e., residential, commercial or industrial buildings)(McGrail, 2007; National Interagency Fire Centre, 1996). In real-world use, the HRP needs to be lifted and carried from the fire engine to the target location. Therefore, lifting the HRP from floor level was considered the functional movement of interest. Additionally, a previous study has established the excellent reliability of measuring lower extremity postures using Dartfish for the lift task (Sinden & MacDermid, 2016).

2.4 Data Acquisition.

Video data was previously (Sinden & MacDermid, 2016) captured and recorded by two digital video cameras (JVC HD Everio GZ-VX700, Full HD, AVCHD), which were positioned on individual tripods facing participants in the frontal and sagittal planes. Participants were required to don the whole set firefighter bunker gear (22.7 kg) consisting of a self-contained breathing apparatus (SCBA) (18.1 kg). Based on the literature review(Huiju Park et al., 2015; K. Park et al., 2010; Punakallio et al., 2003; Sobeih et al., 2006), wearing the full bunk gear could significantly change kinematic features during the performance of lift task. In order to develop a practical measurement method, wearing the PPE is critical to simulate the stressful applied condition during this fire-fighting task.

All video files from frontal and sagittal cameras were exported and saved as audio-video interleaves (AVI) format after collection for further analyses using Dartfish ProSuite software.

2.5 Data Extraction

Data extraction was performed by an operator who had completed the requisite Dartfish training sessions, and additional practice sessions on test files prior to undertaking formal data extraction. Both sagittal and frontal video files were uploaded into Dartfish ProSuite software. As the AVI files from the last study were collected as a random order, an Excel Spreadsheet containing video sequential number, participant ID and camera position was used to categorize and identify all video data. Dartfish Analyzer Module was utilized to extract kinematic variables. Two methods were applied for both the Sagittal and Frontal camera positions to extract kinematic data: Angle Tracking and Positional Co-Ordinate Tracking.

2.5.1 Angle Tracking

Defining Trunk and Knee joint Angle.

According to Sinden et al.,(Sinden & MacDermid, 2016) definitions of hip and knee joint angles were as followed;

The knee angle was formed by a line connected the greater trochanter with the lateral femoral epicondyle and a second line connected the lateral femoral epicondyle with the lateral malleolus. The hip joint angle was the angle structured by connecting a straight line from the lateral aspect of the acromion with the greater trochanter and connecting the greater trochanter with the lateral aspect of the lateral femoral epicondyle.

However, all the anatomical landmarks were unable to be placed due to the obstruction caused by bunker gear. Therefore, the pre-defined anatomical landmarks were positioned relatively by identifying characteristics on bunker gear as a reference. Furthermore, methods of extracting the hip and knee angles were refined as follows (Sinden & MacDermid, 2016)

When inspected through the frontal camera, left hip angle was constructed by placing one marker on the left hip as the vertex, standardizing by the bottom reflective stripe of the bunker coat. One line connected the vertex to the lateral aspect of the left shoulder, starting from the Canadian flag on the bunker coat as a reference, and a second line connecting the vertex from the lateral aspect of the participant's left knee (see Figure of hip angles definition).

For the right hip angle viewed from the sagittal plane camera, the marker point considered as the vertex was established at the right hip, using the bottom reflective stripe of the bunker coat as a reference. One line connected the hip with the lateral aspect of the right “shoulder” and the other line linked the vertex with the lateral aspect of the right knee.

When viewed from the frontal camera, the left knee joint angle was formed by placing the vertex, using the marker on the lateral aspect of the left knee as a reference. First line connected this vertex was the marker point on the lateral aspect of the participant’s left foot standardized by the bottom reflective pant stripe, and the second line connecting the vertex with a marker placed at the lateral aspect of the left hip, using the bottom stripe on the coat as a reference (see Figure of knee joint angles).

Tracking Hip and Knee joint Angle.

The start frame was determined by visual inspection when participants initiated movement towards the HRP. The video frame represented first heel strike as the participant initiated walking towards the frontal camera position or sagittal frame was considered as the end frame. By setting the start frame as the Cue in time point and the end frame as the Cue out time in Dartfish, wasted video frames containing extraneous motions could be excluded manually.

Within the Dartfish software, all the markers track the specific locations information by recognizing the pixels. Therefore, when tracked marker points representing similar pixels move closely, this function will fail to track the given locations and jump into another random points. Due to the above limitation of Dartfish software, applying the auto-tracker function, markers for tracking angles often deviated from the pre-positioned landmarks and requiring a manual correction. When the deviation occurred, the auto-tracking was suspended, the shifted mark points were re-located to defined positions, inaccurate data was removed from the Data Table and then the Angle tracking feature could be re-activated. The manual corrections need to be facilitated frame by frame (each 0.03 second) to minimize the bias caused by auto-tracking function. All the excel spreadsheet files were incorporated and then uploaded into STATA for further statistical analysis.

2.5.2 Positional Coordinate Tracking

Defining hip position coordinates

The method used to track positional co-ordinate data was similar to the one for angle tracking. Instead of the angle drawing tool, for this method, the “Marker” function has been utilized to track hip and knee co-ordinate positional data during the lifting task while the firefighter wore the PPE. Throughout the entire high-rise lifting task, the posture plane containing vertical coordinate movement maintained the perpendicular position to either the frontal or sagittal camera plane, which meant that there was no rotational angle issue contributing systematic measurement error. Therefore, only the vertical hip position data was analyzed in the current study.

According to the procedure from the previous study (Sinden & MacDermid, 2016), the hip vertical displacement was defined as follows:

For both frontal and sagittal frame, the marker was directly placed over the greater trochanter on the bunker gear to track hip position using the bottom reflective stripe on the coat as a reference. The start frame was determined by visual inspection when participants initiated movement towards the HRP. The video frame represented first heel strike as the participant initiated walking towards the frontal camera position or sagittal frame for participants who were left dominant was considered as the end frame.

By setting the start frame as the Cue "in" time point and the end frame as the Cue "out" time in Dartfish, video frames containing extraneous movements could be excluded manually.

Tracking hip positional coordinates.

Comparing with the unit of angle, degree, the unit for displacement, meter, needs to be standardized due to the perspective error(Paul & Douwes, 1993). A reference stick of known length (0.85m) was placed near the participants to calibrate the coordinate data into meaningful units of measurement in the video.

Linked The Data Table from the Drawing Tools with the Marker, then select ’play’ to enable automatic tracking and recording the y co-ordinates of the joint positions. As mentioned in angle tracking section, the auto track feature was set at "Fast" level (monitoring 20% of the video image). The tracked y coordinates and related time were recorded into a Data Table correspondingly for each frame (every 0.03 seconds). (Sinden & MacDermid, 2016)

A similar methodological challenge still existed for hip positional tracking as the marker often deviated from the defined position during automatic tracking. When this occurred, the manual correction was required. The tracking was suspended by clicking the 'pause', the marker was relocated to correct positions, and then the auto-tracking feature would be re-activated.

A significant strength of applying the positional coordinates tracking method compared with the angle tracking was requiring less manual corrections when multi-planar movement happened. The manual correction was conducted subjectively based on professional experience. When the auto tracking finished, the Data Table including vertical positional displacement and time code was exported into an Excel spreadsheet. All the excel spreadsheet files were incorporated and then uploaded into STATA for further statistical analysis.

2.6 Data Analysis

All the Excel spreadsheet including angles and positional coordinates were consolidated and imported to STATA formatted as '.dta' file. All measures were calculated using STATA v13.1 (StataCorp, College Station, TX, USA).

2.6.1 Measures

Lower Extremity Postures

Summary statistics of angles (degree) and positional data (meter) extracted from separate frames using two individual methods is presented in Table 2. Kinematic information in table 2 illustrates the movement requirement of the lower extremity to perform a high-rise pack lifting task. Data obtained from the Frontal Camera position represents left hip and knee joint angle and positional co-ordinate data; right lateral kinematics was obtained from the Sagittal Camera position. In order to describe the range of motion for knee and hip joint angles during lifting task, arc of motion (maximum angles-minimum angles) has been used for both knee and hip joint angles. Lower extremity postures were described using knee, hip joint arc of motion (maximum angles-minimum angles), hip vertical displacement and the displacement normalized by individual height. “Left” indicated the lower extremity kinematics viewed from the frontal frame. Right” indicated the lower extremity kinematics viewed from the sagittal frame.

Lower extremity movement patterns including both individuals and total sample are presented in Figure1-12. Due to the variations of individual task performance times, motion pattern graphs of whole sample cannot be established and analyzed. (Supplementary figure 1). Four data points determined by critical time points during lifting task have been selected to facilitate the movement pattern graph. ‘Begin’ was the beginning of lift task. ‘Reach’ represented the time point when the firefighter’s hand first touched the HRP placed on the floor. ‘Stand’ was the initiation of standing up. ‘Over’ indicated the end of the lifting task.

When the firefighters’ hands touched the HRP, their posture plane was approximately perpendicular to the frontal plane camera. According to J.A Paul et al.,(Paul

& Douwes, 1993) this position could help researchers to minimize the magnitude of perspective error caused by rotational angle. In addition, at the same time, hip and knee joint angles reach the maximum flexion angles, considered as vulnerable position ((OHSCO), 2007; Sinden & MacDermid, 2016).

Hip Joint Vertical Displacement

Hip joint vertical displacement was calculated from the difference value between maximum and minimum vertical hip displacement using y-axis positional coordinate data.

Relative Hip Vertical Displacement

With the consideration of investigating whether or not individual body factor could influence the lower extremity motion during lifting task. The displacement of hip joint vertical positions was standardized by participant height to obtain the relative hip displacement.

Relative hip displacement (%) = (Maximum - Minimum y axis positional coordinate data) (m) / individual height (m)*100

Maximum and Minimum y axis positional coordinate data are the largest and smallest value of the vertical hip displacement during whole lifting task.

2.6.2 Statistical Analyses

Analysis was conducted using Stata, version 14 (StataCorp, College Station, TX, USA). Descriptive statistics were calculated as means and standard deviations for continuous variables, and scatter plots between variable pairs in the database were initially generated to facilitate a visual inspection of the correlations amongst all variables. Shapiro-Wilk test was applied to check the normal distribution assumption, and then the assumption of multivariate normality for correlation was assessed by Doornik-Hansen test. In order to compare how the individual factors influenced the relationship, vertical hip joint displacement and normalized vertical hip joint displacement were inserted to the regression equation separately as dependent variables. Arc of motion of knee and hip joint angles and individual factors, such as age (years), gender, firefighter rank (dummy coded as 0 or 1), weight(kg) and tenure(years) were inserted in to the hierarchical model selection. Three regression strategies including forward, backward and stepwise strategies were applied to fit a relatively precise regression model. The significant level for entrance into the stepwise model was set at $p<0.05$ and $p>0.20$ for removal, to investigate all the potential independent variables. Once a preliminary model was developed, regression diagnostics including tests for homogeneity of variances, normality of residuals, and variance inflation were introduced. Other measures, such as transformation and centering, were applied to remedy any violation of regression assumptions. By checking the leverage versus residual scatter plot and the cook's distance value (Supplementary figure 2 and 3), the extreme outliers were removed after checking the original data and corresponding Dartfish video files for potential errors. The parsimonious model (larger R-squared value) was preferred. Reviewing the regression from a geometric perspective, the scatter plot for multiple linear regression was three-dimensional or more. Consequently, a web-based, 3-D graphic technology was introduced to establish corresponding multi-planar plot for this study. According to Green et.al (Samuel B. Green, 1991), when the number of predictors in the regression model with medium effect size (approximately 0.80)is less than 7, the sample size for study should be larger than $50 + 8m$ (m is the number of predictors). Evaluating the sample size using this requirement, forty-eight subjects were insufficient as the potential predictors in the current study were four. To inspect the stability of the model caused by relatively small sample size, the test for internal validation was introduced. It was checked through 400 bootstrap samples that distributed data from the original sample into two random samples. Both samples were mathematical surrogates used in calculating shrinkage value instead of the pre-designed experimental samples. Shrinkage value was calculated by subtracting the mean R-squared of the first random sample from the mean R-squared of the second samples and dividing by R-squared from the original model.

Once the regression model was established, strengthen of relationship between dependent variable and independent variables was checked using Pearson correlation and partial correlation coefficients. All statistical tests were 2-tailed and an effect was considered significant if $p<0.05$.

3. Result

3.1 Demographics

The participant sample (n=48) for this study represented male (n=42) and female (n=6) active firefighters with a mean age of 42.96 (±8.83) years and 15.86 (±8.70) years of firefighting service. Gender-based analyses of demographics indicated that male firefighters were older, taller, weighed more and had more experiences of service then their female colleague in correlated sections (see Table 1). Male firefighters held the rank of Firefighter (74%) and Captain (26%); 100% of female participants held the rank of Firefighter.

	Age (years)	Height (m)	Weight (kg)	Tenure (years)
Male (n=42)	43.95(8.83)	1.79(0.09)	97.51(11.08)	15.86(8.70)
Female (n=6)	36(5.44)	1.70(0.08)	70.99(12.58)	7(3.62)
Overall(n=48)	42.96(8.84)	1.78(0.09)	94.20(14.23)	14.75(8.73)

Table 1

3.2 Lower extremity kinematics

Left lower extremity (frontal camera). Applying the angle tracking data extraction method viewed from the frontal camera position, to perform the high-rise pack lifting task, the required average arc of motion was 83.90° for left knee joint angles ranging from 20.7° to 136.60° and 107.52° for hip joint angles ranging from 50.46° to 140.36°. Meanwhile, the average hip joint vertical displacement was 0.44m for the left side accounting for 24.52% of the individual height. Minimum vertical displacement was 0.18, maximum was 0.74 amongst whole sample.

Right lower extremity (sagittal camera). Descriptive statistics of the right knee and hip kinematics viewed from the sagittal camera position using the angle tracking data extraction method were: mean arc of motion of knee joint angle was 96.27, (153.42° maximum to 41.50° minimum) and for right hip joint angle was 76.37° (maximum 162.92°, minimum 28.51°). Using positional tracking data extraction methods, the vertical change in right hip joint was 0.48m, accounting for 26.97% of participant height

	Average Left/Right	Maximum Left/Right	Minimum Left/Right
Knee angle (°) Arc of motion	83.90 / 96.27	136.60 / 153.42	20.71 / 41.50
Hip angle (°): Arc of motion	107.52 / 76.37	140.30 / 162.92	50.46 / 28.51
Hip Vertical Displacement (m)	0.44 / 0.48	0.74 / 0.71	0.18 / 0.10
Relative Hip Vertical Displacement (%)	24.52 / 26.97	38.79 / 38.81	10.27 / 5.79

Table 2

3.3 Lower extremity movement patterns

Left lower extremity postures patterns

Visual inspection of lower extremity postures was facilitated by graphing four critical data points, governed by the a priori selection rules (see Measures section 2.6.1). Individual graphs contain all participants' specific pattern line in one figure. Movement pattern of left knee joint angles (degrees) for all individuals are presented in Figure 1.

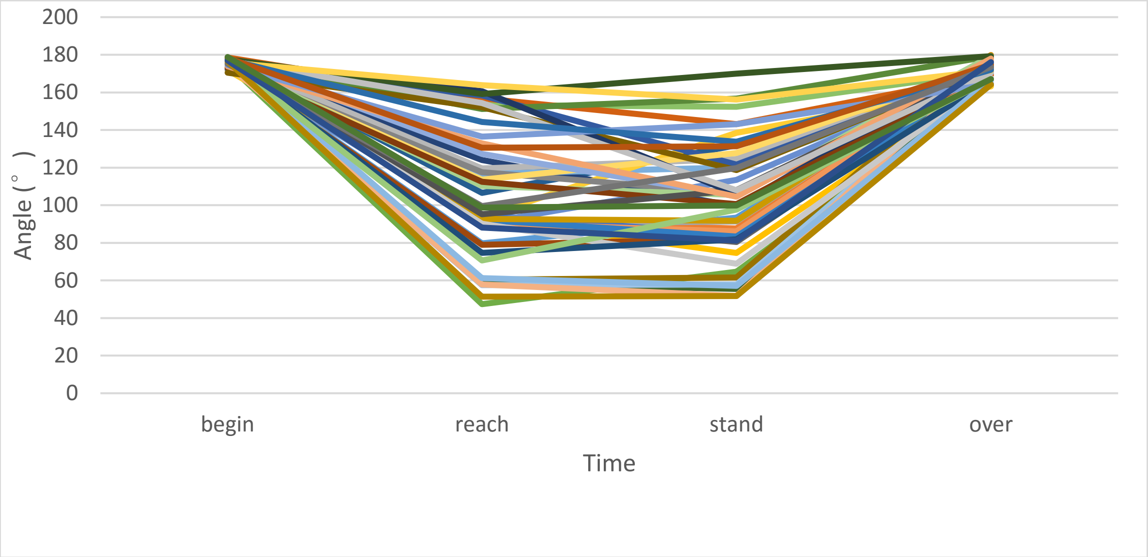


Figure 1

In terms of the sample movement pattern for left knee joint angle, the average value of each critical data point of whole sample has been calculated and graphed. The value of the angles at the beginning and over the task were close, while reach and stand were also very similar (see Figure 2).

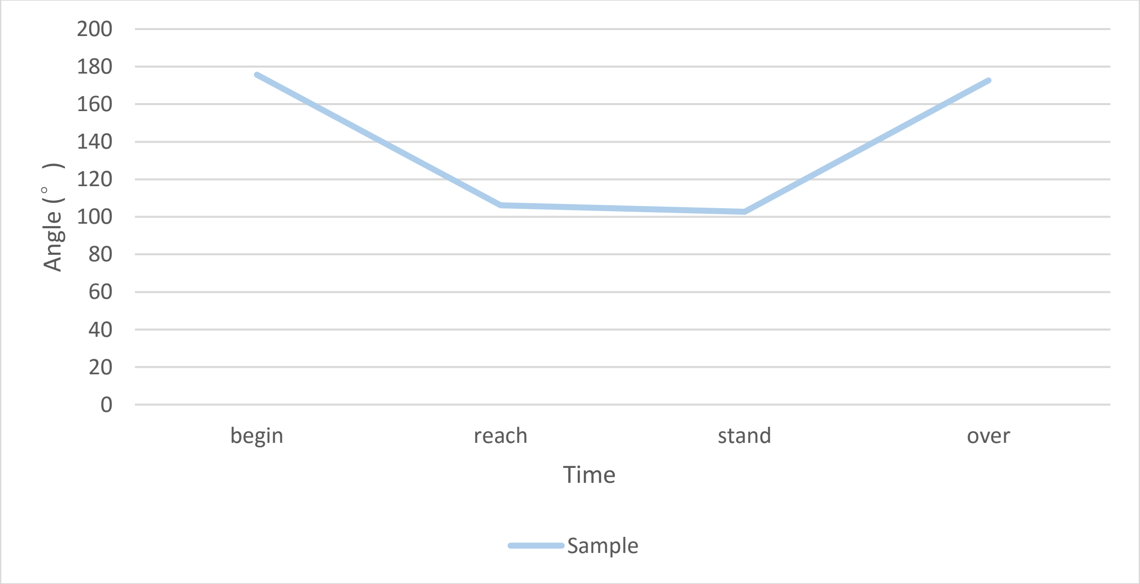


Figure 2

Applying the same procedure, movement graphs for left hip joint angle were listed as followed. (Figure 3,4)

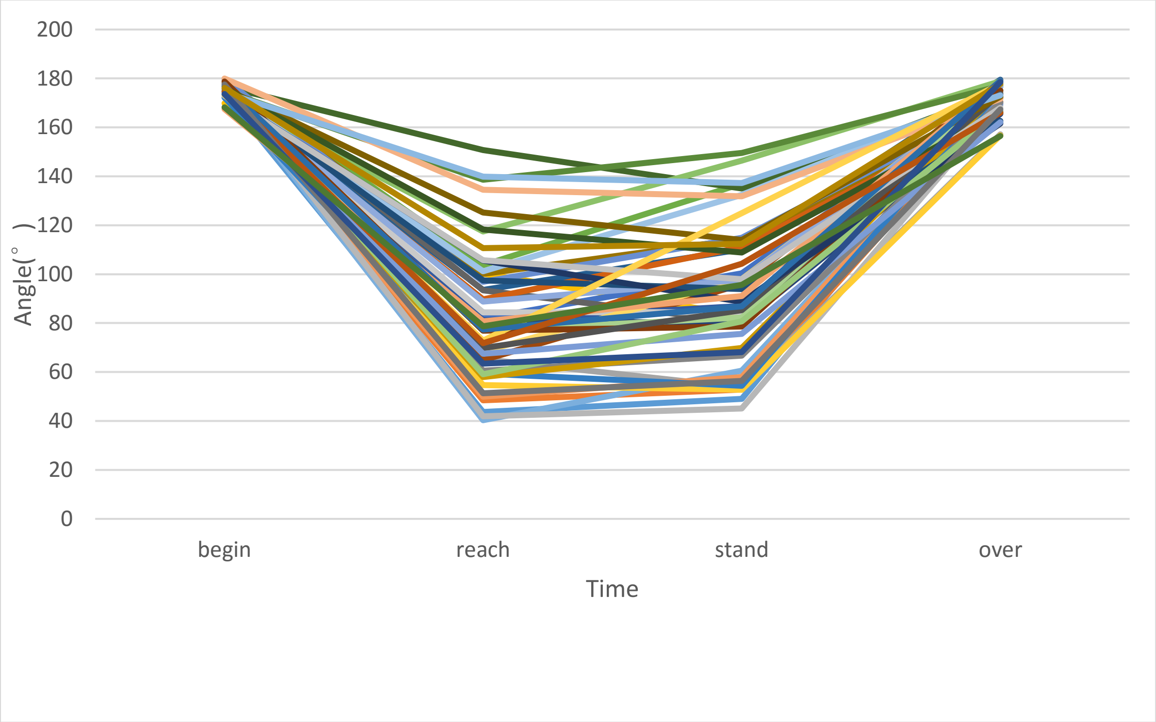


Figure 3

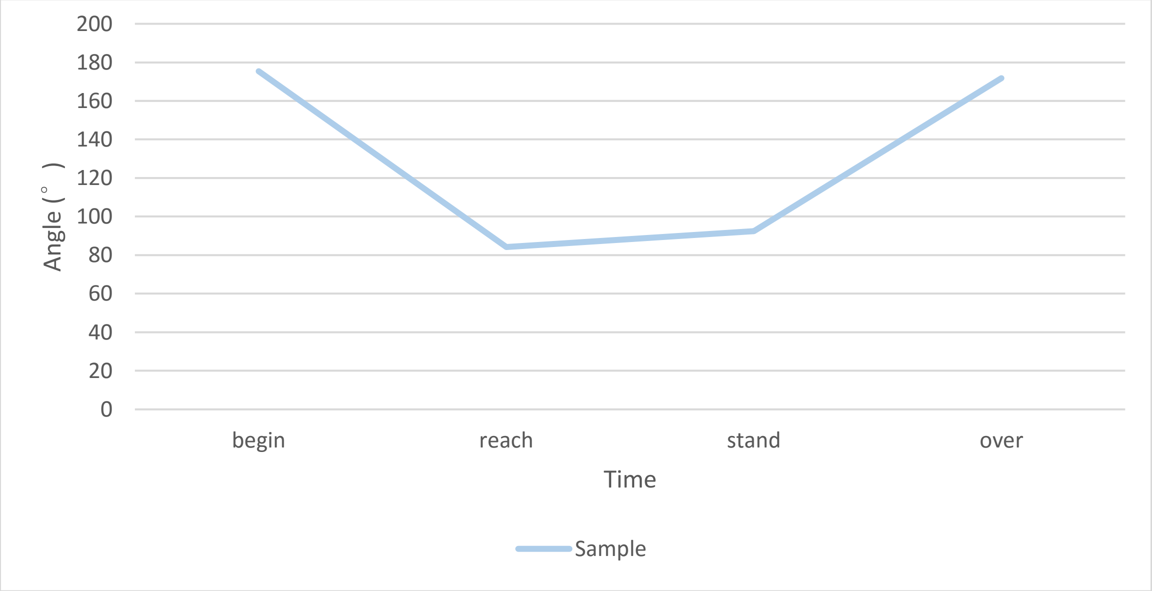


Figure 4

Instead of presenting the joint angles, real-time distance (meters) was used to graph the hip joint vertical displacement (Figure 5, 6).

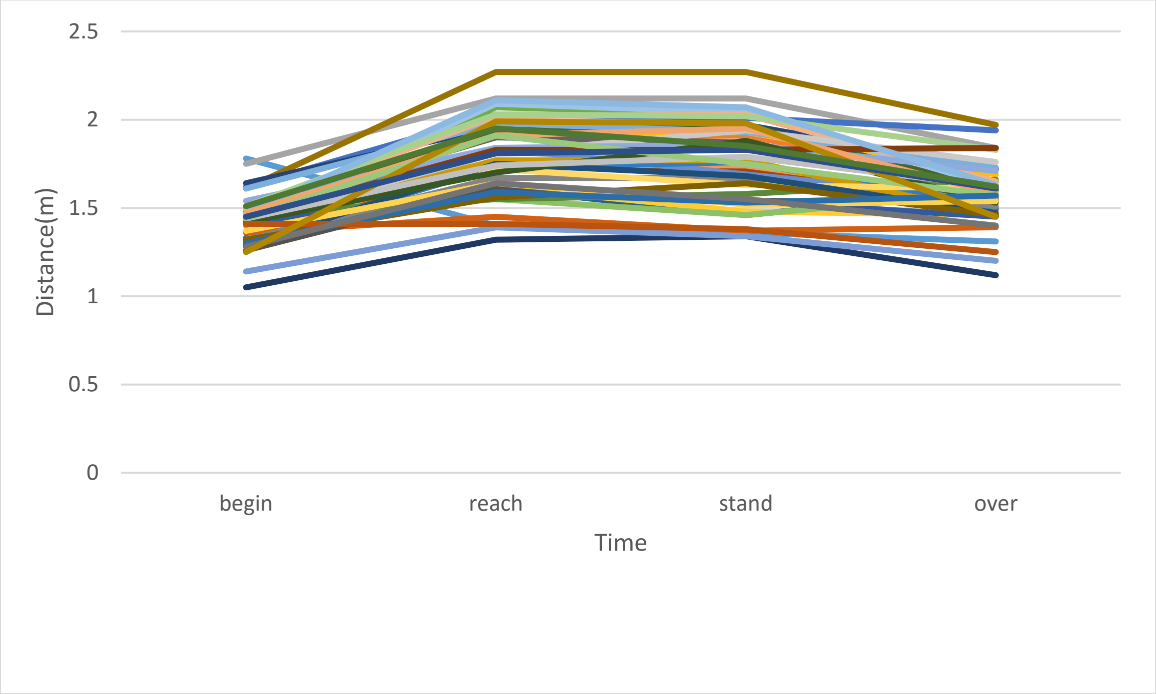


Figure 5

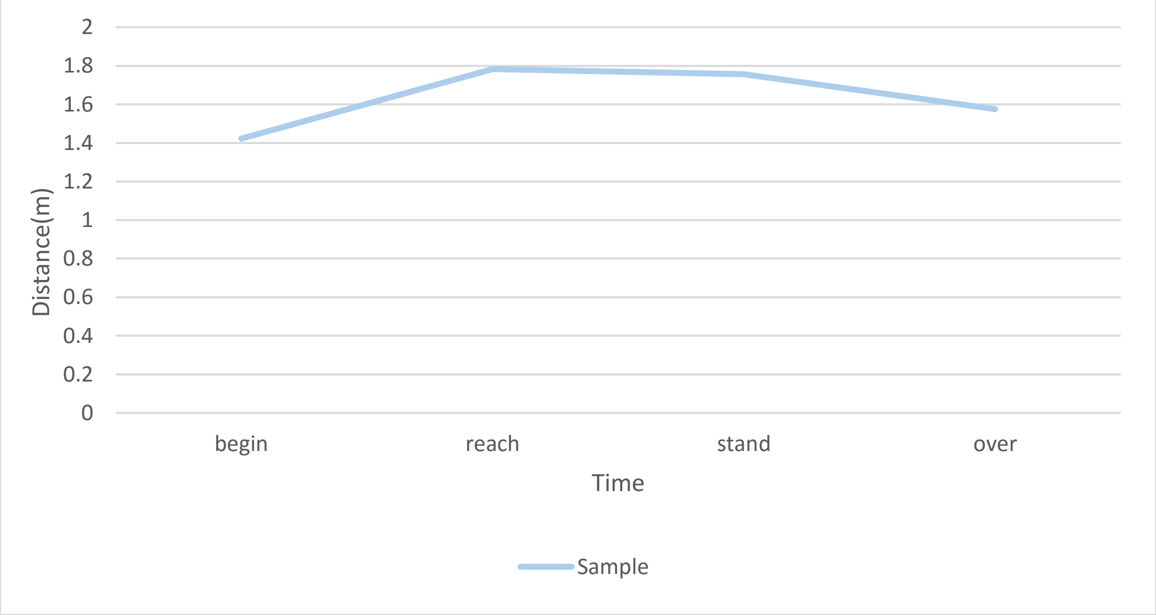


Figure 6

Right lower extremity postures pattern

For right lower extremity, the same methods have been conducted as left side to graph the movement patterns. These are presented graphically in Figures 7 and 8 for the right knee joint angles for all individuals and the overall sample, respectively.

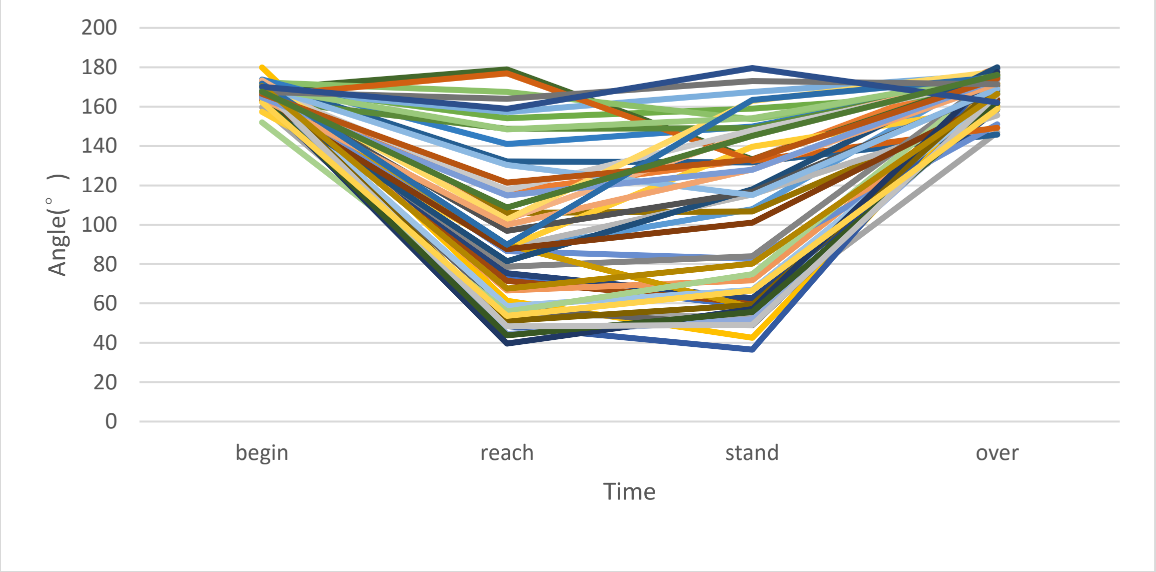


Figure 7

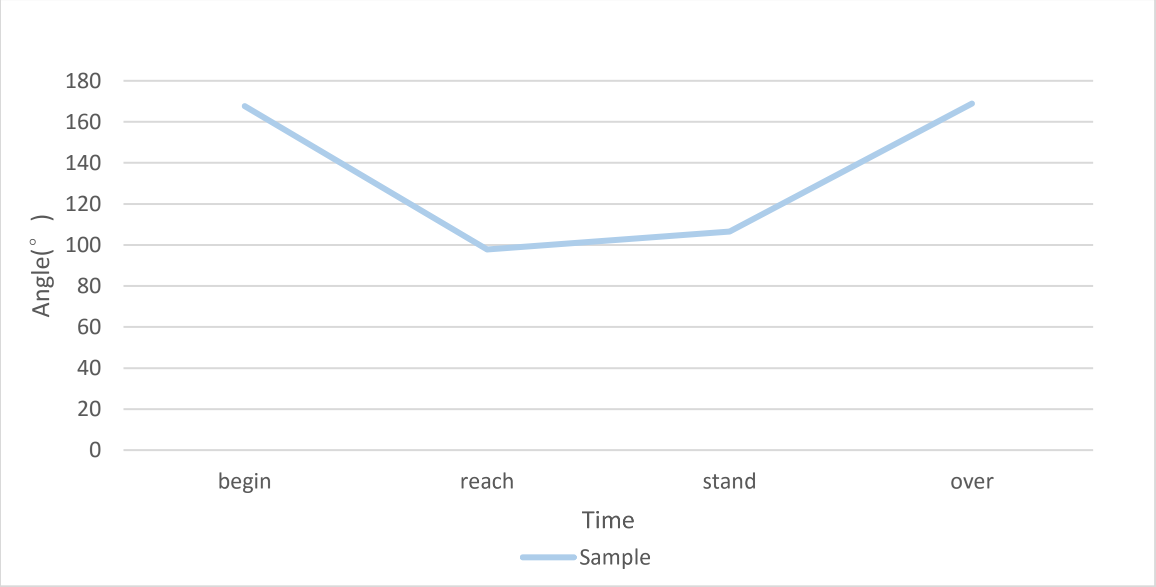


Figure 8

Right hip joint angle was illustrated in Figure 9 for individuals and Figure 10 for whole sample.

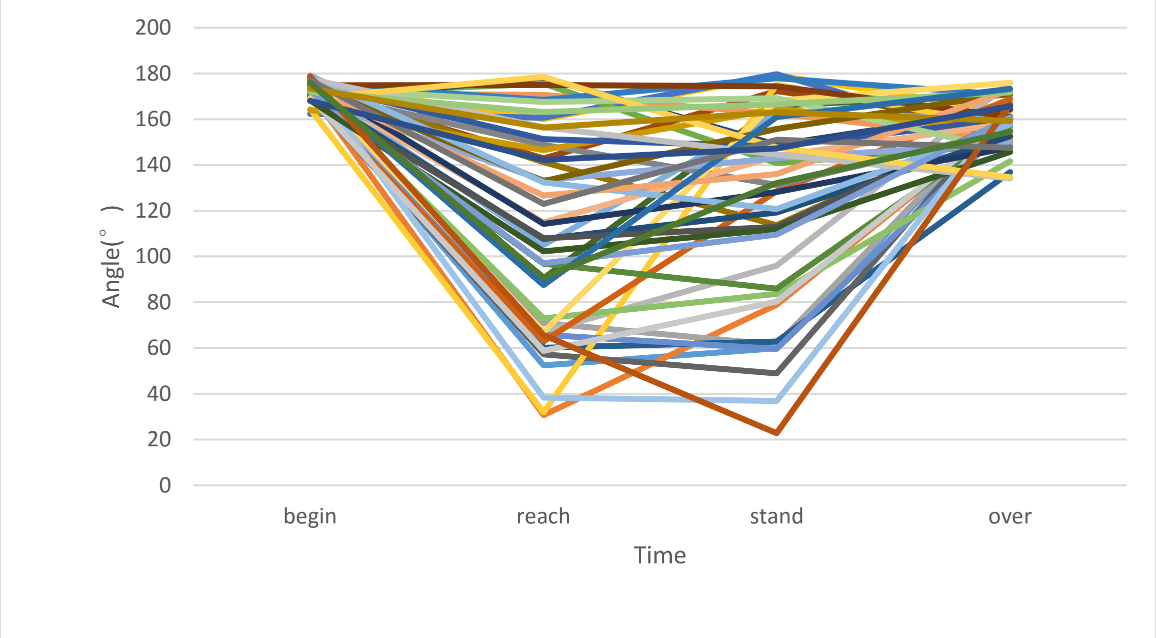


Figure 9

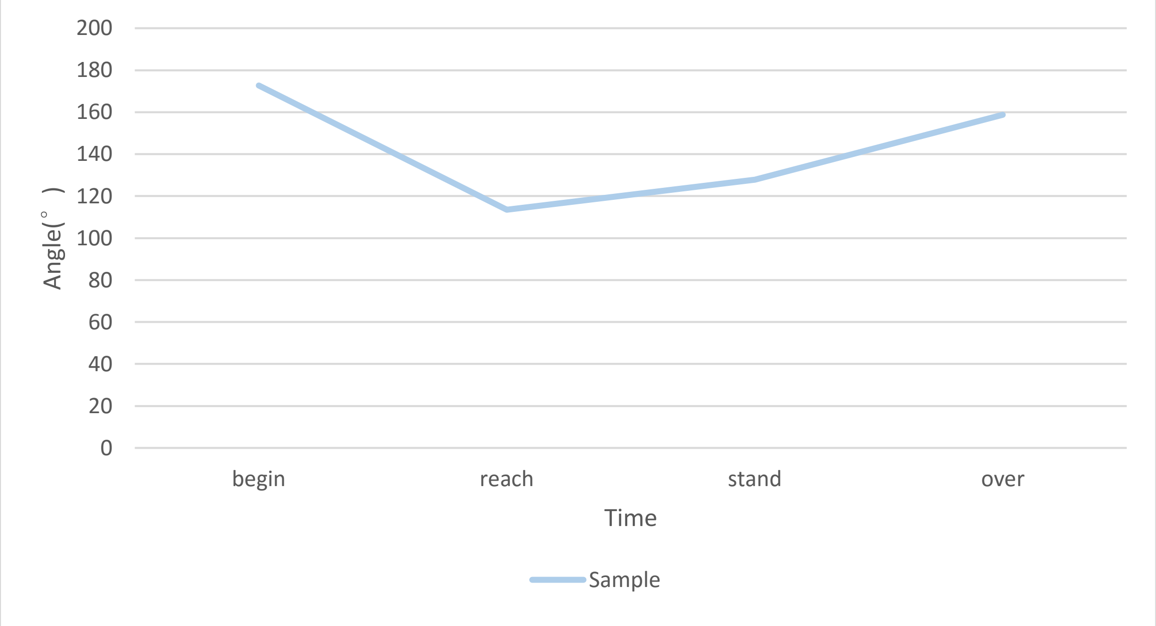


Figure 10

Right side vertical hip joint displacement was displayed using real-time hip vertical distances in Figure 11 for individuals and Figure 12 for sample.

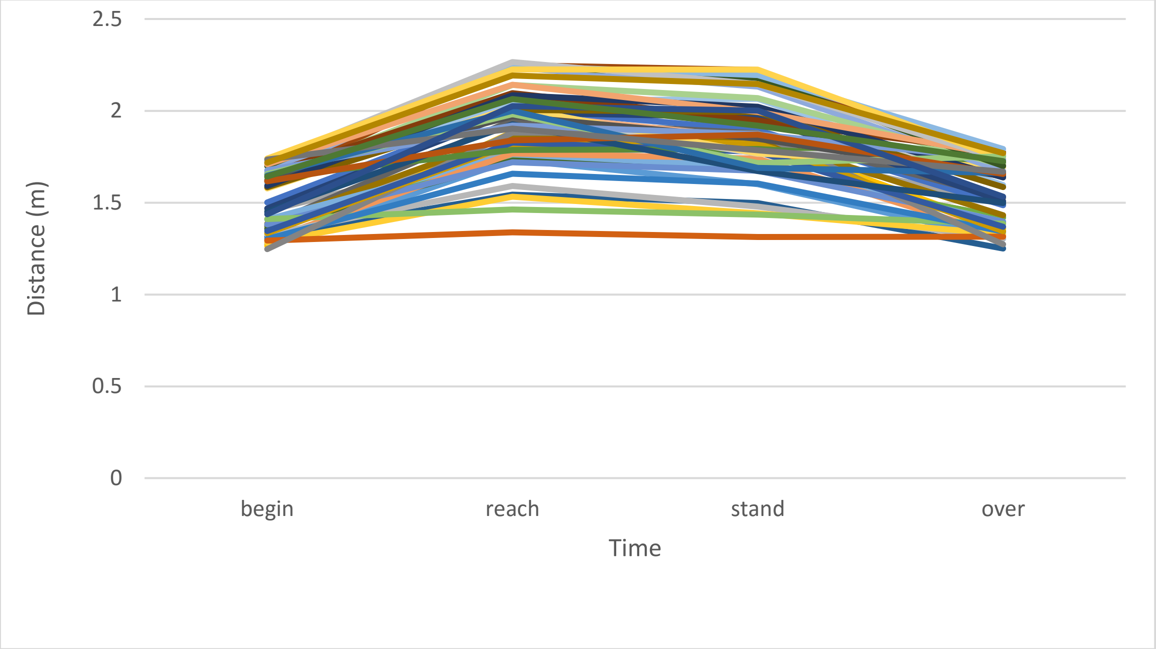


Figure 11

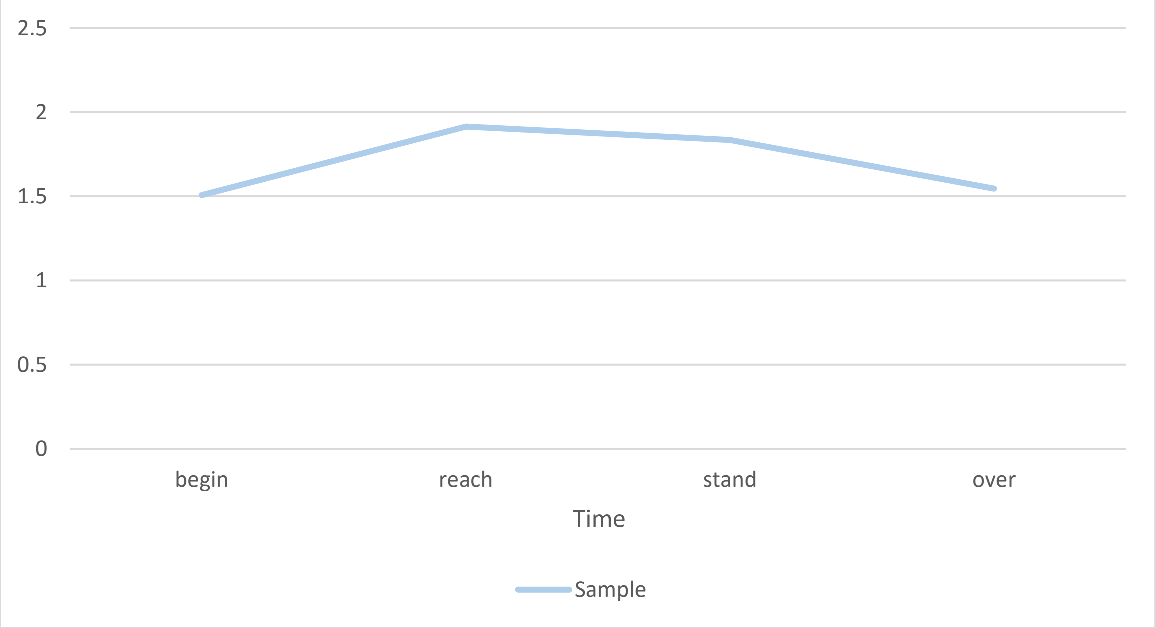


Figure 12

3.3 Multiple regression models

For both the left and right lower extremity postures, four regression models were constructed to explore the relationships between the movement and demographic variables. Vertical hip joint displacement and normalized vertical hip joint displacement were considered dependent variables in the regression model, as the variable of interest in current study.

Left lower extremity regression model

Table 3 presented the first group of comparison between two different dependent variables.

Unstandardized vs Standardized by Height	Beta value	95% Confidence Interval	T-value (p-value)	Unstandardized
				Standardized by Height
Knee Arc of motion (degree)	0.34 0.18	0.26~0.42 0.13~0.22	8.78* 7.99*	Y=0.34*knee-0.07*hip+22.65 R-squared=0.66 Shrinkage=0.09
Hip Arc of motion (degree)	-0.07 -0.04	-0.18~0.03 -0.09~0.02	1.43(p=0.16) 1.23(p=0.23)	Y=0.18*knee-0.04*hip+13.36 R-squared=0.62 Shrinkage=0.10
Constant value	22.65 13.36	8.44~36.87 5.23~21.48	3.21* 3.31*	

Table 3

"*" indicated the significant correlated relationship. ($p<0.05$).

After conducting the regression selection, hip joint angle have been found non-significant in the multiple regression model for both dependent variables. P-value of hip joint angles was 0.16 for unstandardized y and 0.23 for standardized; both were non-significant. However, from a clinical perspective, hip and knee joints movements contributed together to perform the whole high-rise lifting task. Therefore, hip joint angle has been kept in both regression models. R-squared was 0.66 for unstandardized hip joint vertical displacement, which means approximately 66% of the variance could be explained by the current model. Similar value of R-squared has also been obtained which was equal to 0.62. Shrinkage value for both models were less than 10% indicating models could be applied on across a broader population. Furthermore, second set of comparisons, including the demographic variables as potential independent variables is listed in Table 4.

Unstandardized vs Standardized by Height	Beta value	95% Confidence Interval	T-value (p-value)	Unstandardized
				Standardized by Height
Knee Arc of motion (degree)	0.35 0.18	0.27~0.43 0.14~0.23	8.94* 8.43*	Y=0.35*knee-0.08*hip-0.11*weight+33.13 R-squared=0.68 Shrinkage=0.14 Remove id=14, 24, 47 R-squared=0.79 after diagnostic
Hip Arc of motion (degree)	-0.08 -0.04	-0.19~0.02 -0.10~0.01	1.63(p=0.11) -1.53(p=0.13)	
Weight (kg)	-0.11 -0.09	-0.27~0.06 -0.18~0.004	-1.32(p=0.20) -2.16(p=0.04)	Y=0.18*knee-0.04*hip-0.09*weight+21.98 R-squared=0.65 Shrinkage=0.15 Remove id=8, 24, 47 R-squared=0.77 after diagnostic
Constant value	33.13 21.98	11.76~54.51 10.01~33.94	3.12* 3.70*	

Table 4

"*" indicated the significant correlated relationship. ($p<0.05$).

Amongst all the demographic variables, weight has been kept due to the most significant p-value, especially for height normalized dependent variables (p=0.06). Hip joint angle was still larger than 0.05 for both regression equations. However, the p-value became much more significant, decreasing from 0.23 to 0.13. Although the individual factors have been considered as the predictors. The result for variance inflation check was equal to 1.05 indicating there is no collinearity existing in independent variables based on the Rule-of-Thumb (Samuel B. Green, 1991). The other assumption of multiple linear regressions, constant variance across the independent variables was confirmed by performing Breusch-Pagan test. Through applying the Shapiro-Wilk test on the residuals of dependent variables, it suggested the normality assumption for the dependent variable was violated. However, a histogram graph of residuals confirmed this violation was very mild, as the visual depiction of the dependent variable appeared normally distributed. To improve the stability and predictive power of the regression model, Cooks-distance and scatter plot of residuals and leverage was introduced to expose the outliers. After reviewing the original Excel and video files, three extreme outliers were found. An attempt was made to improve the predictive power of the regression equation by excluding three outliers. After the requisite diagnostics, both regression models including weight as an independent variable have a nearly 10% increase in the R-squared value. The final regression equations for frontal frame were:

Hip vertical displacement =0.34*knee-0.07*hip+22.65

Height normalized hip vertical displacement =0.18*knee-0.04*hip+13.36

Hip vertical displacement =0.35*knee-0.08*hip-0.11*weight+33.13

Height normalized hip vertical displacement=0.18*knee-0.04*hip-0.09*weight+21.98

Right lower extremity Regression Model

Regression models were constructed following the same procedures described above; the resultant regression equations for right side lower extremity are listed in Table 5 and Table 6.

The regression model including only knee and hip joint angle for right lower extremity was derived from the stepwise selection. Comparing with the frontal frame, the p-value for both knee and hip joint angle were significant this time. However, predictive power of the regression model decreased from 66% to 39% for the unstandardized dependent variable and from 62% to 41% for the height standardized one.

Different significant indicator has been found through stepwise selection for right side lower extremity regression models. Instead of weight, 'age' was retained in the final model after the selection procedure. Comparing with the previous models, R-square increased slightly for both equations. Regression diagnostics did not find collinearity or heteroskedasticity. The assumption of normal distribution of the dependent variable was met by inspecting the histogram visually. Subsequently, four extreme outliers were excluded from the whole sample. R-square increased slightly after the exclusion.

The final regression equations for sagittal frame were:

Hip vertical displacement = 0.14*knee-0.14*hip+44.99

Height normalized hip vertical displacement = 0.09*knee-0.08*hip+24.13

Hip vertical displacement =0.12*knee-0.16*hip-0.35*Age+33.49

Height normalized hip vertical displacement = 0.18*knee-0.04*hip-0.09*Age+21.98

Unstandardized vs Standardized by Height	Beta value	95% Confidence Interval	T-value (p-value)	Unstandardized
				Standardized by Height
Knee Arc of motion (degree)	0.14 0.09	0.02~0.27 0.02~0.15	2.33* 2.67*	Y=0.14*knee-0.14*hip+44.99 R-squared=0.39 Shrinkage=0.18
Hip Arc of motion (degree)	-0.14 -0.08	-0.25~-0.04 -0.13~-0.02	-2.77* -2.88*	Y=0.09*knee-0.08*hip+24.48 R-squared=0.41 Shrinkage=0.12
Constant value	44.99 24.48	27.26~62.72 14.89~34.06	5.11* 5.08*	

Table 5

"*" indicated the significant correlated relationship. (p<0.05)

Unstandardized vs Standardized by Height	Beta value	95% Confidence Interval	T-value (p-value)	Unstandardized
				Standardized by Height
Knee Arc of motion (degree)	0.12 0.07	-0.001~0.24 0.007~0.14	1.99(p=0.05) 2.23*	Y=0.12*knee-0.16*hip+0.35*Age+33.49 R-squared=0.43 Remove id=14, 35,42, 44 R-square=0.54 after diagnostic Shrinkage=0.33
Hip Arc of motion (degree)	-0.16 -0.10	-0.27~-0.06 -0.15~-0.04	-3.17 -3.44*	
Age (years)	0.35 0.23	-0.03~0.74 0.02~0.45	1.85(p=0.07) 2.22*	Y=0.07*knee-0.10*hip+0.23*Age+16.95 R-squared=0.49 Shrinkage=0.26 Remove id=28, 35,42, 44 R-square=0.59 after diagnostic
Constant value	33.49 16.95	12.16~54.83 5.50~28.40	3.17* 2.99*	

Table 6

"*" indicated the significant correlated relationship. (p<0.05)

3.2 Bivariate Correlation Analysis

The bivariate correlation relationship was indicated by Pearson correlation coefficient. Bivariate normality assumption for Pearson correlation was investigated by the Doornik-Hansen test. Through the normality check, weight was not significantly correlated with hip vertical displacement and relative hip vertical displacement for both left and right lower extremity. Meanwhile, hip joint angle has been found non- significantly correlating with the height-normalized displacement for the frontal frame, which was already indicated in the previous regression model. Based on Rosnow et al.,(Rosnow & Rosenthal, 1989) the effect size of 0.30 could be considered as a moderate power of correlation and 0.50 could be evaluated as a strong relationship. For left lower extremity, the arc of motion of the knee joint angle has a strong correlating relationship with both hip vertical displacement(r=0.81) and the one standardized by height(r=0.78). However, hip joint angle has been found only moderately correlated with hip vertical displacement (r=-0.30). Furthermore, while weight was not significantly correlated with both dependent variables, it was included in the regression model as a predictor by the stepwise selection. To explore the inconsistency, partial correlation was introduced. As a result, the r value for weight was increased by controlling weight for the arc of motion of knee and hip joint angle. The correlation between weight and height standardized hip joint vertical displacement also became significant by checking the partial correlation. All details were listed in Table 7

Correlation	Hip Vertical Displacement		Hip Vertical Displacement Standardized by Height	
	Frontal frame	Sagittal frame	Frontal frame	Sagittal frame
Knee joint angle arc of motion	0.81*	0.54*	0.78*	0.57*
Hip joint angle arc of motion	-0.30*	-0.56*	-0.27	-0.58*
Weight	-0.05	0.22	-0.04	0.14
Age	-0.03	0.19	-0.02	0.23
Weight Control for arc of motion	-0.20	0.15	-0.31*	0.05

Table 7
"*" indicated the significant correlated relationship. ($p<0.05$).

4. Discussion

The current study was identified hip and knee postures of firefighters lifting a high-rise pack from floor to shoulder while wearing full bunker gear, and ta model multiple linear regression model that chacterized the relationship amongst the kinematic variables. The arc of motion of knee and hip joint angles were identified to describe the requirement of lower extremity postures performing the high-rise lifting task. In addition, lower body movement patterns for both individuals and the whole sample were illustrated by line graphs. Furthermore, regression analysis of kinematic variables also demonstrated that there was significant relationship existing amongst kinematic variables, which were extracted from video-based inputs through both frontal and sagittal camera positions using

Dartfish angle tracking and positional tracking extraction methods during an applied firefighting task. The following discussions of each finding incorporate the limitations of this study.

Lower extremity postures

Cross plane movement analysis was an important issue to this 2D measurement, requiring cautious interpretation. Participants were asked to begin the lifting task in a pre-defined position facing the frontal camera. For standardization, the HRP was positioned to the right side of each participant. Subsequently, movement analysis viewed from the sagittal camera position included most of the participants rotating toward a transverse plane, which was paralleled to the sagittal camera to touch the HRP causing a frontal plane perspective analysis; conversely, video inputs captured from the frontal camera position involved participants rotating into a sagittal perspective.

Our study results for angle tracking of knee and trunk angles identified that firefighters required a maximum 136.60° of right knee flexion and a minimum 20.71° of left knee flexion; a maximum 153.42°(standing position) of knee flexion and a minimum 41.50° of right knee joint angle to transfer the HRP from floor to shoulder level. These findings suggested that firefighters required from 83.90° to 96.27° of both left and right knee range-of-motion during the completion of lift task. With the consideration of preventing possible work-related injuries, this outcome provided the basic, task-based, range-of-motion guidelines. When comparing the hip joint angles from sagittal plane with the one from frontal camera planes, a disparity has been found as the arc of motion of hip joint angle was 107.52° for the left side and 76.37° for right lateral. This 31° difference between left and right hip joint arc of motion indicated that angle tracking measurement may not precisely detect the hip joint angle viewed from the sagittal frame due to hip joint movement was at the parallel plane to the sagittal camera. This finding is contradictory to previous studies reporting a high level of reliability of using Dartfish (Sinden & MacDermid, 2016), and correlated relationships between the 2D and 'gold standard' 3D measures when measuring right knee and pelvic angle during a jumping task (Eltoukhy et al., 2012; Maykut et al., 2015). However, comparing with other firefighters' movement analysis studies, the current study was conducted under a less controlled experimental setting without multiple cameras and force plates. Taken together, these results suggested that lower extremity angles measured from a parallel plane to the camera frame using a 2D measurement approach should be cautiously analyzed or combined with other related kinematic variables. The study results supported the capacity of 2D motion measurement to be extended to identify firefighter posture and kinematics under an occupational research context. Future study could examine this 2D angle tracking method by comparing the result obtained from Dartfish software with the 3D movement analysis system under a similar applied context during same lift task.

To understand the relationship between hip vertical displacement (standardized and unstandardized) and other kinematics variables, and to interpret this relationship from a clinical perspective, anatomical positional tracking was used to evaluate relative hip vertical displacement. Comparing with the measurement error caused by applying angle tracking method, such as subjective more manual corrections and inconsistency reliability

(B. Norris & Olson, 2011), the positional co-ordinates method was the favored method to measure the posture kinematics during multi-planar tasks.

The study results suggest that firefighters moved almost one fourth of body height (24.52% of height) to lift the HRP from floor to the shoulder level. Our previous pilot work identified ranging from 19 to 25% (Sinden & MacDermid, 2016). The significant level of the difference was unclear. The larger sample size of forty-eight participants for this study comparing with the twelve participants from last study may be the primary reason to cause the divergence. Another potential reason to explain the issue seems to be the influence of manual corrections during data extraction using Dartfish: re-locating tracking mark points was highly subjective, and a training effect may have emerged with the larger number of corrections applied across a larger sample. In terms of lower extremity movement mechanics, our findings reveal a physical demand of less knee flexion (83.9°), which is calculated by subtracting minimum knee angle from maximum knee angle, and more hip flexion (107.52°) when lifting the high-rise pack from floor to shoulder. These results indicate that considering individual relative hip vertical displacement as a single component of lower extremity posture might provide similar information in terms of lower extremity posture, such as knee and trunk angle kinematics. In addition to identifying the postures, 25% relative hip displacement also indicates an inherent relationship within the lifting task, with a higher range of knee flexion associated with larger hip displacements. To investigate the potential causal or predictive association amongst knee, hip joint angle, and hip vertical displacement (standardized and unstandardized), a multiple linear regression was performed to model the internal relationship.

Correlation and Multiple linear regression analysis

The present study results expand previous research (Huiju Park et al., 2015; Punakallio et al., 2003; Sinden & MacDermid, 2016; Vieira & Kumar, 2004) into a relatively clinical field that investigated the internal relation amongst lower extremity kinematic variables extracted by Dartfish, a reliable measurement approach to analyzing movements during functional tasks in an applied setting. We replicated the measurement properties including two camera positions, two individual data extraction methods and an occupational firefighting task where participants wear PPE. The location of anatomical marks to track hip and knee angles were similar to the protocols in pilot study (Sinden & MacDermid, 2016). Positional coordinates method limiting the usage of marker points for multi-planar movement analysis was conducted according to the methods recommended by Sinden et al (Sinden & MacDermid, 2016).

Four sets of regression models were developed to address the secondary objectives. For both left and right lower extremity, the value of R-squared are similar when considered hip vertical displacement and height normalized hip vertical displacement as two separate dependent variables. More specifically, viewed from the frontal frame, R-square is 0.66 for unstandardized and 0.62 for height standardized. The same condition has been found in the regression models containing individual factors (0.68 vs 0.65 for left side). However, the change of independent variables should be treated carefully.

Through the stepwise selection, weight has been included as an independent variable for left lower extremity and age for right extremity. Interestingly, those added individual factors both have a non-significant p-value before normalizing the dependent variable by height (p=0.20 of weight for left and p=0.07 of age for right). Utilizing the height normalized dependent variables, weight and age became statistically significant. This raises several interesting questions: 1) why does weight influence only the movements on the left side of the body, while age only influences the movements on the right? (as indicated by the regression models) 2) What is the explanation for the change in p-value after normalizing the dependent variable?

These findings need to be evaluated by considering the video capture and data extraction procedures. The most interesting postures (bending, touching the HRP and standing up) on the left side of the body during the high-rise lifting task were exposed distinctly to the frontal camera since the frame containing the lifting movement was perpendicular to the frontal frame. As acknowledged previously, manual corrections for the deviation could bring the bias into tracking data due to the subjective nature of the procedure. Besides the measurement error coming from the methodology challenge, nearly 25% of the R-square difference (0.68-0.43) also supported the conclusion that right side lower extremity kinematics extracted from the sagittal frame were relatively inaccurate compared with the left lower extremity kinematics extracted from the frontal camera.

Further insights can therefore be gained by considering the regression models generated by the frontal frames. Within the context of current study, the Pearson correlation coefficient between height and weight was much higher than the one between height and age (0.43 vs 0.03), which should also explain the reason the reader should focus on the left side lower extremity models. Furthermore, partial correlation was conducted to expose the change in weight between unstandardized dependent variable and standardized one.

Controlling the arc of motion of knee and hip joint angles, r indicating the partial correlation relationship was equal to -0.20 for the hip vertical displacement and -0.31 for the height normalized one. Coming with the increase in r value, p-value became statistically significant which could explain the change in p-value of weight after considering height normalized vertical hip joint displacement as the dependent variable in the regression model. Therefore, height and weight contributes together in our regression model.

Although hip joint angle was non-significant in the initial regression model as an independent variable, it was still retained in future models because of the clinical relevance. On one hand, the hip and knee joint contribute together to perform this lifting task. On the other hand, we found a significant Pearson correlation between the arc of motion of hip joint angle and hip vertical displacement ($r=-0.30$, $p<0.05$). Consequently, this regression model can be explained meaningfully in kinematic terms that the flexion angle range of the squatting movement caused by bending at knee has a positive relationship with the body vertical displacement, as well as the extension movement.

As an attempt to obtain a better regression model with higher power, regression diagnostics have been conducted; three extreme outliers (id=14, 24, 47) were excluded from the original model for left side lower extremity with individual factors. We found nearly 10% increase in the R-square after the diagnostic. The criterion for excluding outliers was dependent on the visual inspection of the leverage versus residual plot and the calculation of cook's distance. The cut off points for cook's distance was equal to '4 / sample size' based on the Rule of Thumb. According to the same rules, four extreme outliers (id=14, 44, 37, 41) were removed for the right lower extremity regression model with individual factors. Approximately 6% increase has been found in both equations. Although the power of regression models were increased by regression diagnostics, the results need to be applied with caution for the following reasons: a) the sample size has been reduced manually after diagnostic; b) the judgment about exclusion was a subjective decision, especially for the leverage vs. residual plot, and c) Individual cases would be excluded.

Although 4% of shrinkage value for frontal frame regression equation indicates the model is stable with internal validation compared with the acceptable level (10%) based on the rule-of-thumb, there are several reasons to interpret these results with caution. Firstly, comparing with previous studies (Maykut & Ford, 2015; B. S. Norris & Olson, 2011), our sample size is much larger. However, based on the sample size calculation, 48 participants seems to be not enough to obtain stable cross-fit power. Furthermore, outliers are subjectively excluded depending on the scatter plots and Cook's distance. Both of the above reasons could cause the "overfit" issue of regression models. For the left side, lower extremity regression models included only hip and knee joint angles, shrinkage values are 0.09 and 0.10. These values increased to 0.14 to 0.15 when the individual weight was included in the model considered as independent variable. All the above results indicate our regression model could be applied on more generalizable study samples. Conversely, the regression models for right side hip and knee postures are much larger than the left side, which supports the finding that our sagittal frame kinematics need to be improved.

With the consideration of facilitating the interpretation of study findings in terms of relative hip displacement in a clinical perspective, Pearson and Spearman correlation has been used to obtain a preliminary impression of the internal relationship between relative hip displacement and knee and trunk angles. The moderate correlation coefficients have been found from both frontal and sagittal frame using parametric and non-parametric statistical analysis. However, these coefficients cannot be utilized to interpret the internal association amongst variables as they simply indicate the strength of the relationship, not the predictive or causal nature of the relationship.

Clinical implications

This study extends the finding of previous studies into a clinical field by investigating relationships between vertical hip displacement and hip and knee flexion angles in a population of active firefighters during a lifting task while wearing full personal protective equipment. The sample recruited in this study consists of both male and female firefighters who experience highly physical requirements of fire-fighting, intense work schedules, a hazardous working environment and stressful mental demands. The risk of suffering work-related injury is high in this population, but a limited number of kinematic studies have been conducted on this target population because of the complexity of analyzing the fire-fighting task. Based on previous work (Sinden & MacDermid, 2016), the relative hip vertical displacement derived from the positional coordinates tracking method shows better relative reliability than the angle information extracted by the angle tracking method. However, it is difficult to interpret the relative hip displacement by itself in a clinical way. This limitation of 2D measurement is partially addressed as the regression models of current study provide adequate power to complement the information provided by individual angles using the relative hip displacement data when the multi-planar movement happens during the performance of the given task. Therefore, based on the lower extremity kinematics obtained from the current study, ergonomists could understand the mechanisms behind fire-fighting tasks and then establish a movement posture guideline of occupational task to strategize the prevention plan of work-related musculoskeletal disorder for firefighters. Furthermore, portable devices with the application of Computer-Human Interaction technology enables firefighters to acknowledge the real-time parameters in terms of physical demand and postures standards during applied task.

Dartfish software is a reliable movement analysis tool providing users with various functions enabling them to identify movement characteristics during occupational tasks. (Khadilkar et al., 2014; Sinden & MacDermid, 2016). Further examinations extending the findings of the current study need to examine the model of right side lower extremity postures with caution before application.

Strengths and Limitations

Primarily, our study is unique in that it a) uses a previously validated 2D measurement system, Dartfish, to identify lower extremity postures during an occupationally relevant fire-fighting task and b) investigated the internal relationship amongst kinematic information by applying regression statistical analysis. Specifically, we simplify the procedure of manipulating two data extraction methods (angle tracking and positional coordinates) and thereby improve the precision of the data. Furthermore, a considerable number of statistical technologies including matrix scatter plot, Pearson & Spearman correlations, multiple linear regression, regression diagnostic, bootstrap sampling and cross validation have been conducted in the current study to ensure the statistical power of the final model. Therefore, our regression model could provide useful dynamic and systemic kinematic information enabling other researchers formulating the prevention strategy of firefighting-related injuries.

According to the data extraction procedure in our study, to facilitate analyzing lower extremity postures using Dartfish, several suggestions have been listed as followed:

a) Calibrating the image with multiple subjects of known dimension in the immediate plane of the participants (Body height, length of the stick, and box position).
b) Setting up the start and end frame using cue in & out function to simplify the data extraction procedure. More specifically, Angle tracking and Single frame analysis method could be switched by identifying different start frame.
c) Utilizing the ‘left control’ and ’right arrow’ to check the tracking feature frame by frame (0.03s) before collecting data.
d) Due to the reduced reliability issue using the Angle tracking method to extract data of multi-planar movement. Relative hip vertical displacement derived from positional coordinates tracking method can be considered as an important parameter to describe the lower extremity postures based on the regression model of our study.

The most important limitation of this research is the relatively small sample size. This could result in an insufficient power to identify potential predictors. Since this is a secondary analysis study, we cannot recruit more participants to increase the power of the regression analysis. Bootstrap sampling has been conducted to test the internal-validation and indicated a generalizability issue existing in the regression model for left-side lower extremity postures. Future research needs to apply the model on various populations with caution.

The second limitation of this study is to interpret the internal relationship using our regression model due to cross-sectional study design. That means our regression could not be interpreted as causation, but as association. That is to say, increased arc of motion of knee joint angle, decreased arc of motion of hip joint angle are positively associated with function; however, causal relationships cannot be concluded from this result.

Another potential limitation of this study was using the stripe of the firefighter’s coat as a reference to standardize the placement of mark points during analyzing the performance of task. Since the study purpose is to identify the lower extremity kinematics using Dartfish in an applied context. The precision of data extraction methods becomes quite important. Despite the fact that two data extraction methods have been utilized to improve the accuracy of the data, a better standardization methodology needs to be developed. For example, adding an aerial view camera can help researchers to quantify the rotational angle and then modify the perspective error of tracking angles by specific equations. Within the Dartifsh software, interested joint angles or positions will be highlighted automatically. In terms of both angle tracking and positional coordinates, required manual corrections could be limited.

Future research focusing on the upper extremity identifying and modeling the upper extremity postures in occupational contexts can be used to confirm the study findings in our study and extend this measurement and regression model to assessing whole body movements.

5. Conclusion

The purpose of this study was to apply Dartfish two-dimensional movement analysis software to identify firefighters' trunk and knee postures during a firefighting lift task while wearing PPE and to subsequently model multiple linear regression relationships among the kinematic variables generated. Lower extremity postures and hip vertical displacement during an occupational fire-fighting task has been characterized followed the data extraction procedure in previous research (Sinden & MacDermid, 2016). Although the regression model was established, power and shrinkage value of the model for the sagittal plane was considerably low. Future research should validate the regression model on upper extremity and increase the sample size to obtain more statistical power before applying the model to identify the whole body movement.

6. Reference List

(OHSCO), O. H. and S. C. of O. (2007). Musculoskeletal Disorder (MSD) Prevention Guideline for Ontario.

Allen, J. L., James, C., & Snodgrass, S. J. (2012). The effect of load on biomechanics during an overhead lift in the WorkHab Functional Capacity Evaluation. *Work (Reading, Mass.)*, *43*(4), 487–96. http://doi.org/10.3233/WOR-2012-1386

Borel, S., Schneider, P., & Newman, C. J. (2011). Video analysis software increases the interrater reliability of video gait assessments in children with cerebral palsy. *Gait & Posture*, *33*(4), 727–9. http://doi.org/10.1016/j.gaitpost.2011.02.012

Butler, R. J., Plisky, P. J., Southers, C., Scoma, C., & Kiesel, K. B. (2010). Biomechanical analysis of the different classifications of the Functional Movement Screen deep squat test. *Sports Biomechanics*, *9*(4), 270–279. http://doi.org/10.1080/14763141.2010.539623

Dempsey, P. G., & Mathiassen, S. E. (2006). On the evolution of task-based analysis of manual materials handling, and its applicability in contemporary ergonomics. *Applied Ergonomics*, *37*(1 SPEC. ISS.), 33–43. http://doi.org/10.1016/j.apergo.2004.11.004

Eltoukhy, M., Asfour, S., Thompson, C., & Latta, L. (2012). Evaluation of the Performance of Digital Video Analysis of Human Motion: Dartfish Tracking System. *International Journal of …*, *3*(3), 1–6. Retrieved from http://www.ijser.org/researchpaper/Evaluation_of_the_Performance_of_Digital_Video_Analysis_of_Human_Motion.pdf

Gregory, D. E., Narula, S., Howarth, S. J., Russell, C., & Callaghan, J. P. (2008). The effect of fatigue on trunk muscle activation patterns and spine postures during simulated firefighting tasks. *Ergonomics*, *51*(7), 1032–41. http://doi.org/10.1080/00140130701813178

Holden, S., Boreham, C., Doherty, C., Wang, D., & Delahunt, E. (2015). Clinical Biomechanics Clinical assessment of countermovement jump landing kinematics in early adolescence : Sex differences and normative values. *JCLB*, 6–11. http://doi.org/10.1016/j.clinbiomech.2015.03.008

Hoogendoorn, W. E., Poppel, M. N. M. Van, Bongers, P. M., Bart, W., Bongers, M., & Hoogendoorn, E. (2015). Finnish Institute of Occupational Health Danish National Research Centre for the Working Environment Norwegian National Institute of Occupational Health.

Katayanagi, J., Iida, T., Oyama, Y., Ato, A., Mine, K., Toumura, T., & Ozeki, S. (2015). Sagittal plane alignment evaluation during walking in adult spinal deformity : gait analysis using DARTFISH. *Scoliosis*, *10*(Suppl 1), P21. http://doi.org/10.1186/1748-7161-10-S1-P21

Khadilkar, L., MacDermid, J. C., Sinden, K. E., Jenkyn, T. R., Birmingham, T. B., & Athwal, G. S. (2014). An analysis of functional shoulder movements during task performance using Dartfish movement analysis software. *International Journal of*

Shoulder Surgery, *8*(1), 1–9. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4049033/

Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics*, *44*(1), 17–47. http://doi.org/10.1080/00140130120716

List, M., Directory, D., Open, O. F., & Journals, A. (2010). RESEARCHES CONCERNING THE UTILIZATION OF THE KINEMATIC ANALYSIS MOVEMENT SOFTWARE IN 2D SYSTEM – DARTFISH © IN THE MALE TRIPLE JUMP EVENT TECHNIQUE MONITORING MIHAI Ilie , Faculty of Physical Education and Sport, University of Pitesti, ROMANIA, (2), 2008–2010.

Mahmoud, I., Othman, A. A. A., Abdelrasoul, E., Stergiou, P., & Katz, L. (2015). The reliability of a real time wearable sensing device to measure vertical jump. *Procedia Engineering*, *112*, 467–472. http://doi.org/10.1016/j.proeng.2015.07.226

Maykut, J. N., & Ford, K. R. (2015). Concurrent validity and reliability , *10*(2), 136–146.

Maykut, J. N., Taylor-Haas, J. A., Paterno, M. V, DiCesare, C. A., & Ford, K. R. (2015). Concurrent validity and reliability of 2d kinematic analysis of frontal plane motion during running. *International Journal of Sports Physical Therapy*, *10*(2), 136–46. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=4387721&tool=pmcentrez&rendertype=abstract

McGill, S., Frost, D., Andersen, J., Crosby, I., & Gardiner, D. (2013). Movement quality and links to measures of fitness in firefighters. *Work*, *45*, 357–366. http://doi.org/10.3233/WOR-121538

McGrail, D. M. (2007). *Firefighting Operations in High-Rise and Standpipe-Equipped Buildings*. PennWell Books. Retrieved from https://books.google.com/books?hl=en&lr=&id=esXQpgf7QbcC&pgis=1

McLean, S. G., Walker, K., Ford, K. R., Myer, G. D., Hewett, T. E., & van den Bogert, a J. (2005). Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *British Journal of Sports Medicine*, *39*, 355–362. http://doi.org/10.1136/bjsm.2005.018598

Melton, C., Mullineaux, D. R., Mattacola, C. G., Mair, S. D., & Uhl, T. L. (2011). Reliability of video motion-analysis systems to measure amplitude and velocity of shoulder elevation. *Journal of Sport Rehabilitation*, *20*(4), 393–405. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/22012494

Miller, A., & Callister, R. (2009). Reliable lower limb musculoskeletal profiling using easily operated, portable equipment. *Physical Therapy in Sport*, *10*(1), 30–37. http://doi.org/10.1016/j.ptsp.2008.10.003

National Interagency Fire Centre. (1996). Wildland Fire Suppression Tactics Reference Guide. *National Wildfire Coordinationg Group*, 353. http://doi.org/2004-689-253/603

Norris, B. S., & Olson, S. L. (2011). Concurrent validity and reliability of two-dimensional video analysis of hip and knee joint motion during mechanical lifting. *Physiotherapy Theory and Practice*, *27*(7), 521–30. http://doi.org/10.3109/09593985.2010.533745

Norris, B. S. T., & Olson, S. L. (2011). Concurrent validity and reliability of two-dimensional video analysis of hip and knee joint motion during mechanical lifting. *Physiotherapy Theory and Practice*, *27*(7), 521–30. http://doi.org/10.3109/09593985.2010.533745

Park, H., Trejo, H., Miles, M., Bauer, A., Kim, S., & Stull, J. (2015). Impact of firefighter gear on lower body range of motion Huiju. *International Journal of Clothing Science and Technology*, *27*(2), 315–344.

Park, H., Trejo, H., Miles, M., Bauer, A., Kim, S., & Stull, J. (2015). Impact of firefighter gear on lower body range-of-motion. *International Journal of Clothing Science and Technology*, *27*(2), 315–334.

Park, K., Hur, P., Rosengren, K. S., Horn, G. P., & Hsiao-Wecksler, E. T. (2010). Effect of load carriage on gait due to firefighting air bottle configuration. *Ergonomics*, *53*(7), 882–891. http://doi.org/10.1080/00140139.2010.489962

Parsons, J. L., & Alexander, M. J. L. (2012). Modifying spike jump landing biomechanics in female adolescent volleyball athletes using video and verbal feedback. *Journal of Strength and Conditioning Research*, *26*(4), 1076–84. http://doi.org/10.1519/JSC.0b013e31822e5876

Paul, J. A., & Douwes, M. (1993). Two-dimensional photographic posture recording and description: a validity study. *Applied Ergonomics*, *24*(2), 83–90. http://doi.org/10.1016/0003-6870(93)90079-O

Punakallio, A., Lusa, S., & Luukkonen, R. (2003). Protective Equipment Affects Balance Abilities Differently in Younger and Older Firefighters. *Aviation Space and Environmental Medicine*, *74*(11), 1151–1156.

Rhea, M. R., Alvar, B. A., & Gray, R. (2004). Physical fitness and job performance of firefighters. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *18*(2), 348–352. http://doi.org/10.1519/R-12812.1

Rosnow, R. L., & Rosenthal, R. (1989). Statistical procedures and the justification of knowledge in psychological science. *American Psychologist*, *44*(10), 1276–1284. http://doi.org/10.1037/0003-066X.44.10.1276

Samuel B. Green. (1991). How Many Subjects Does It Take To Do A Regression Analysis. *Multivariate Behavioral Research, 26*(3), 499–510. http://doi.org/10.1207/s15327906mbr2603

Sinden, K. E., & MacDermid, J. C. (2016). 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. *Journal of Ergonomics, 06*(01), 1–10. http://doi.org/10.4172/2165-7556.1000145

Sobeih, T. M., Davis, K. G., Succop, P. a., Jetter, W. a., & Bhattacharya, A. (2006). Postural Balance Changes in On-Duty Firefighters: Effect of Gear and Long Work

Shifts. *Journal of Occupational and Environmental Medicine*, *48*(1), 68–75. http://doi.org/10.1097/01.jom.0000181756.38010.d2

Vieira, E. R., & Kumar, S. (2004). Working Postures: A Literature Review. *Journal of Occupational Rehabilitation*, *14*(2), 143–159. http://doi.org/10.1023/B:JOOR.0000018330.46029.05

Wang, R., Leow, W. K., & Leong, H. W. (2008). 3D-2D Spatiotemporal Registration for Sports Motion Analysis.

Wuensch, K. (2015). Cohen ' s Conventions for Small , Medium , and Large Effects, 25–26.

Table 1. Participant Demographics.

	Age (years)	Height (m)	Weight (kg)	Tenure (years)
Male (n=42)	43.95(8.83)	1.79(0.09)	97.51(11.08)	15.86(8.70)
Female (n=6)	36(5.44)	1.70(0.08)	70.99(12.58)	7(3.62)
Overall(n=48)	42.96(8.84)	1.78(0.09)	94.20(14.23)	14.75(8.73)

Reported as mean (SD).

Table 2. Movement requirements of lower extremity performing the lift task

Changes in joint angle	Average Left/Right	Maximum Left/Right	Minimum Left/Right
Knee angle (°) Arc of motion	83.90 / 96.27	136.60 / 153.42	20.71 / 41.50
Hip angle (°): Arc of motion	107.52 / 76.37	140.30 / 162.92	50.46 / 28.51
Hip Vertical Displacement (m)	0.44 / 0.48	0.74 / 0.71	0.18 / 0.10
Relative Hip Vertical Displacement (%)	24.52 / 26.97	38.79 / 38.81	10.27 / 5.79

"Left" indicated the lower extremity kinematics viewed from the frontal frame.
"Right" indicated the lower extremity kinematics viewed from the sagittal frame.

Figure 1. Left knee joint angles pattern (individuals).

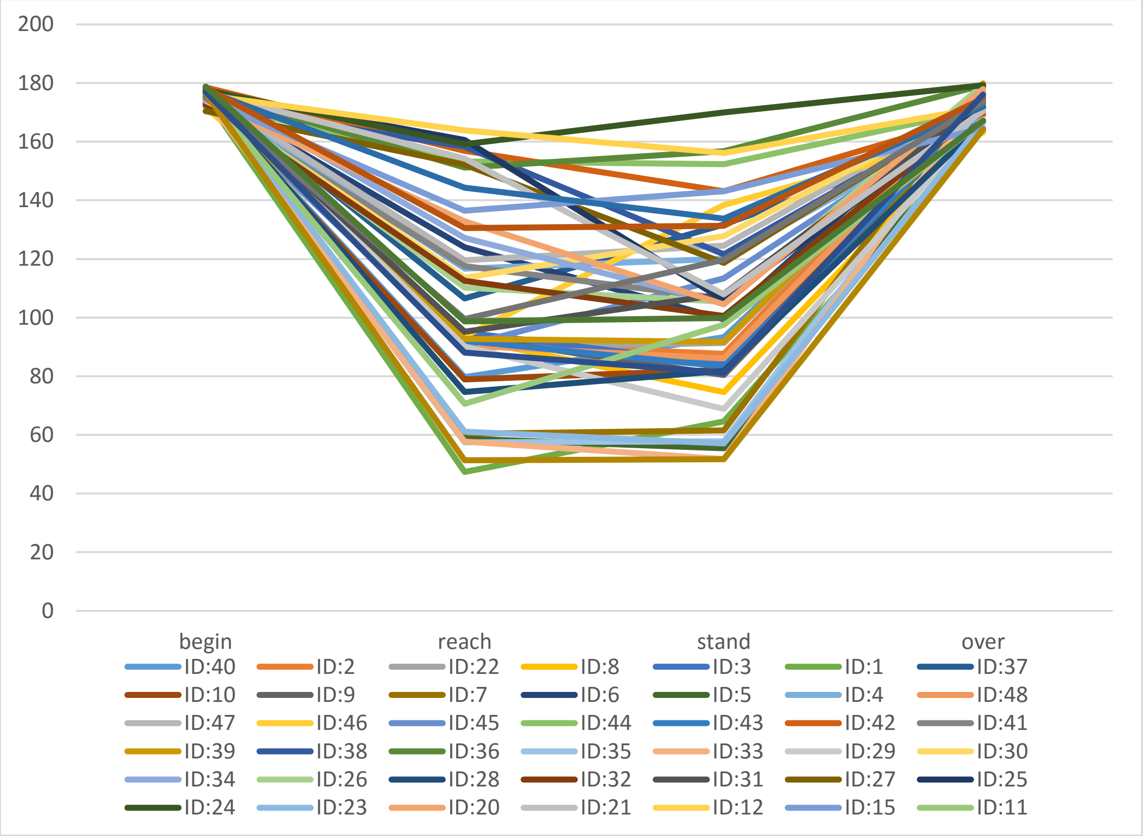


Figure 2. Left knee joint angles pattern (sample).

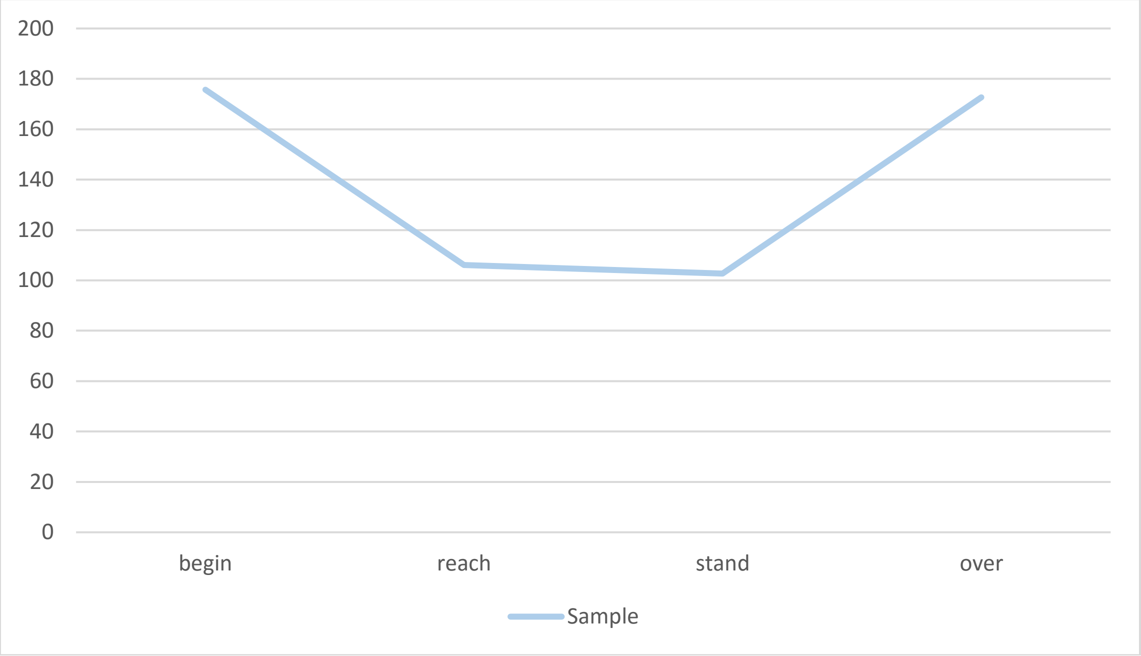


Figure 3. Left hip joint angles pattern (individuals).

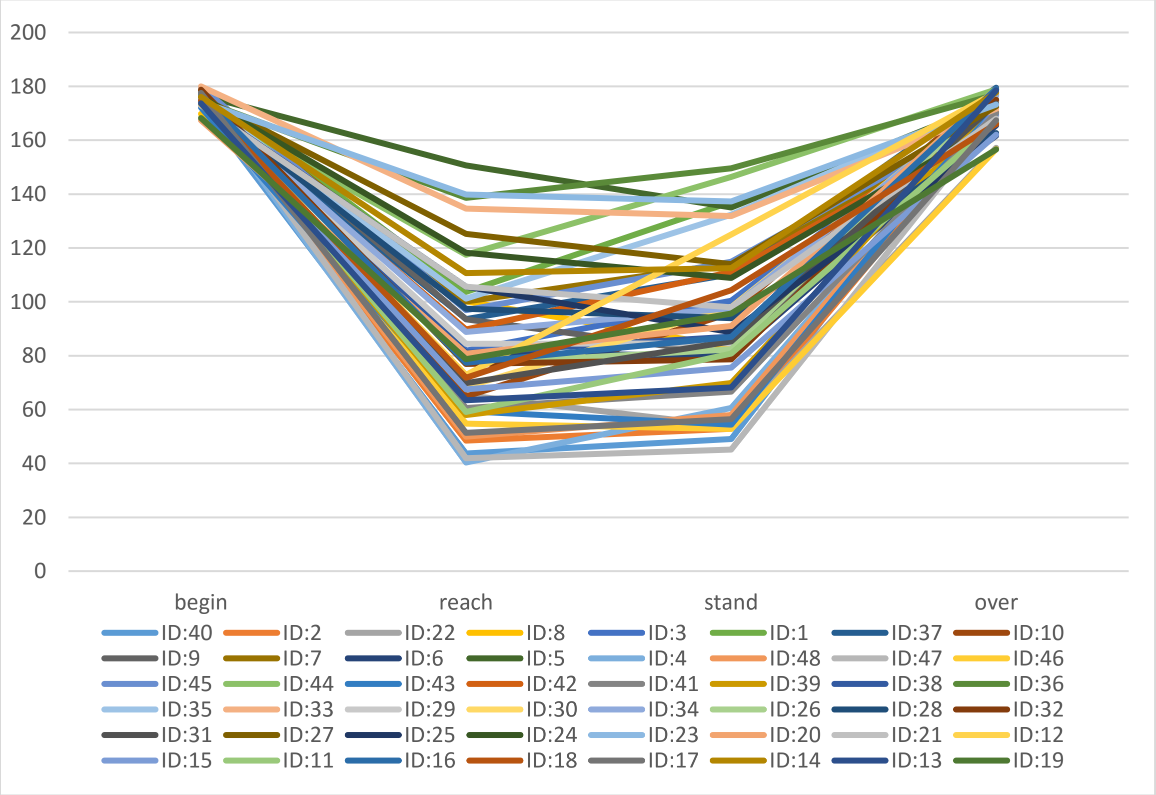


Figure 4. Left hip joint angles pattern (sample).

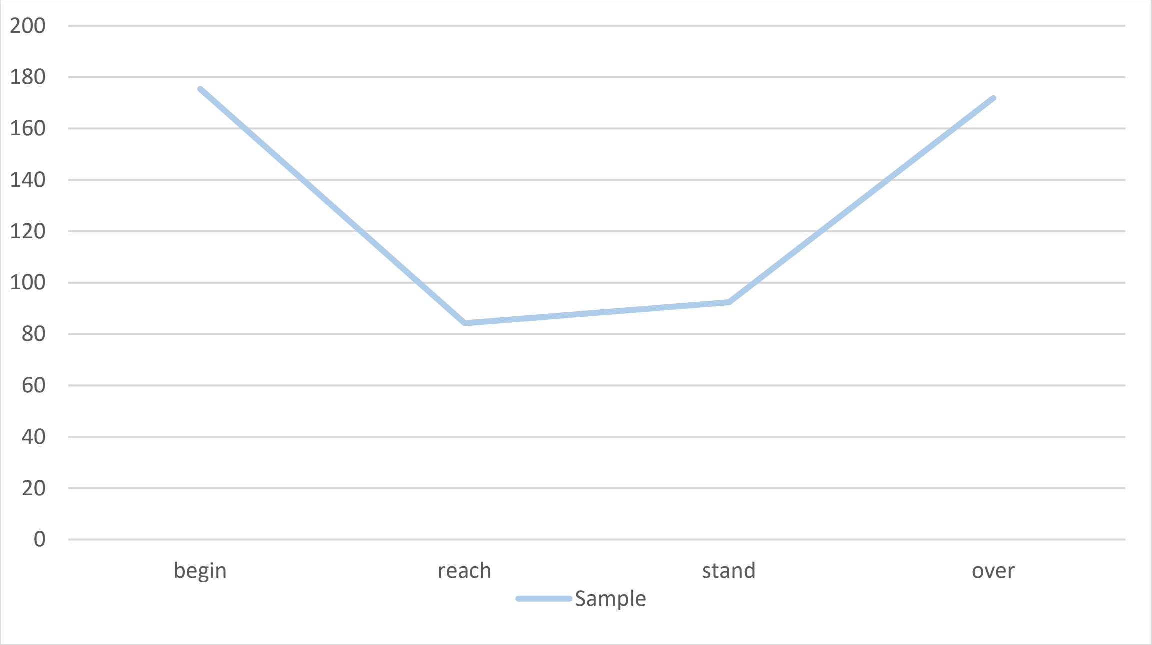


Figure 5. Left hip joint displacement (individuals).

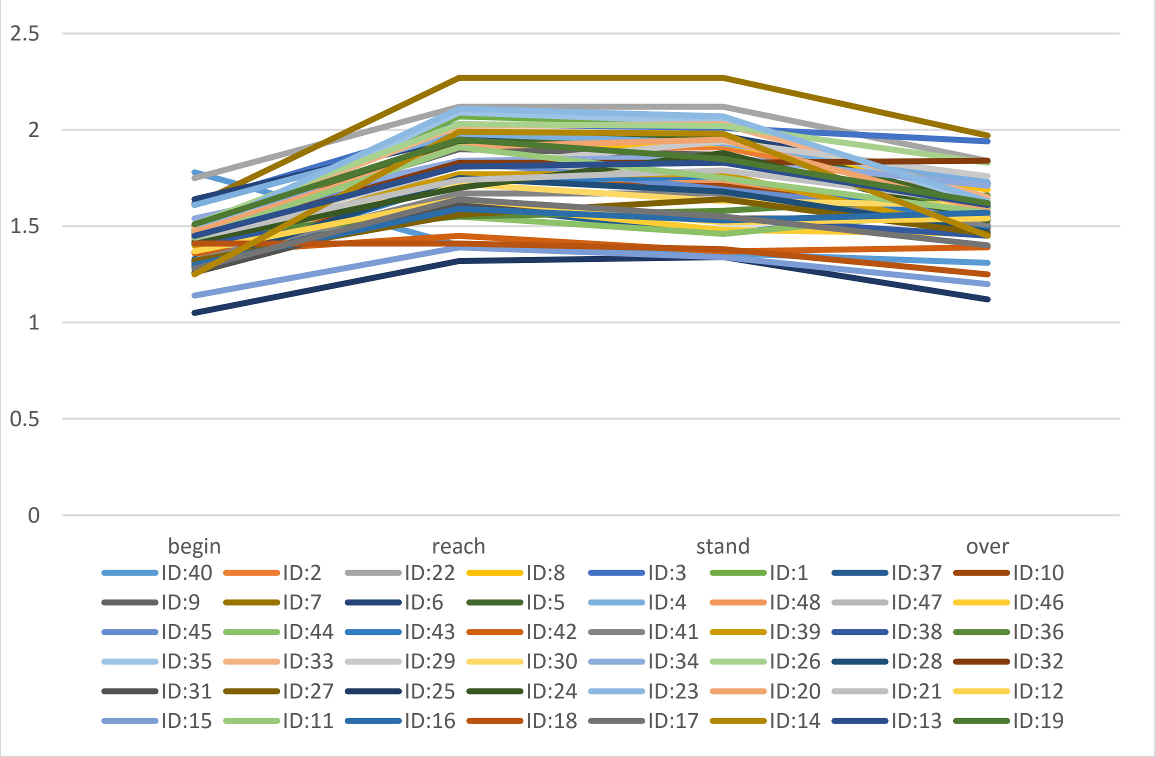


Figure 6. Left hip joint displacement (sample).

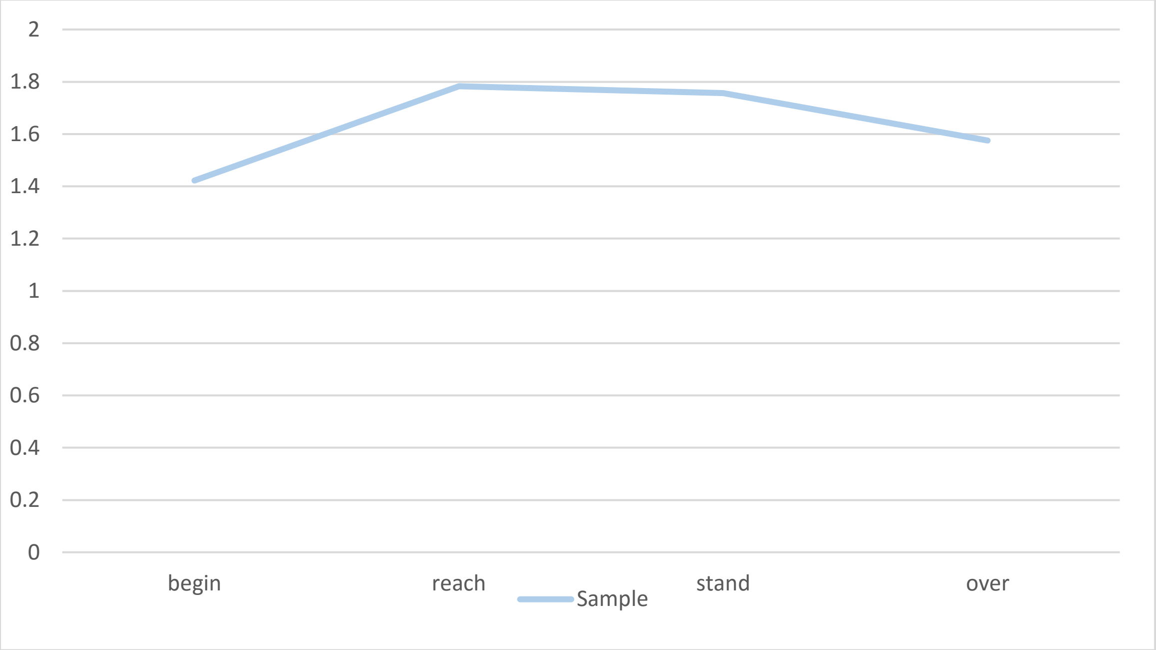


Figure 7. Right knee joint angles pattern (individuals).

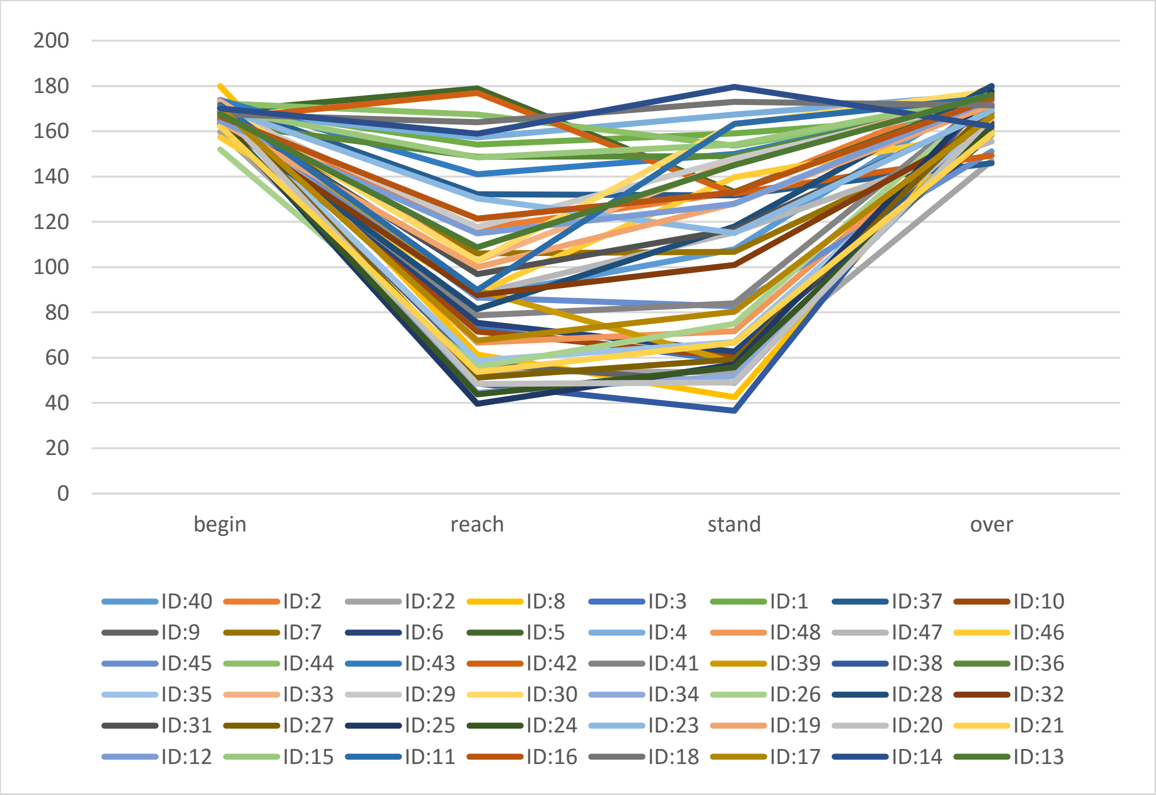


Figure 8. Right knee joint angles pattern (sample).

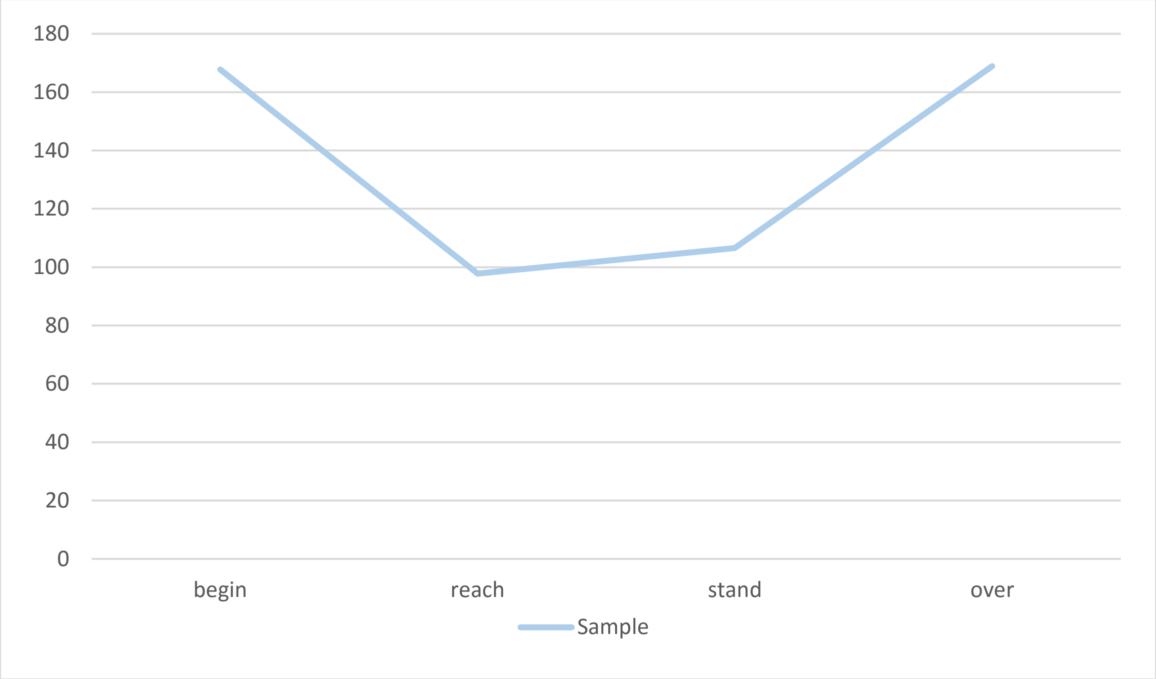


Figure 9. Right hip joint angles pattern (individuals).

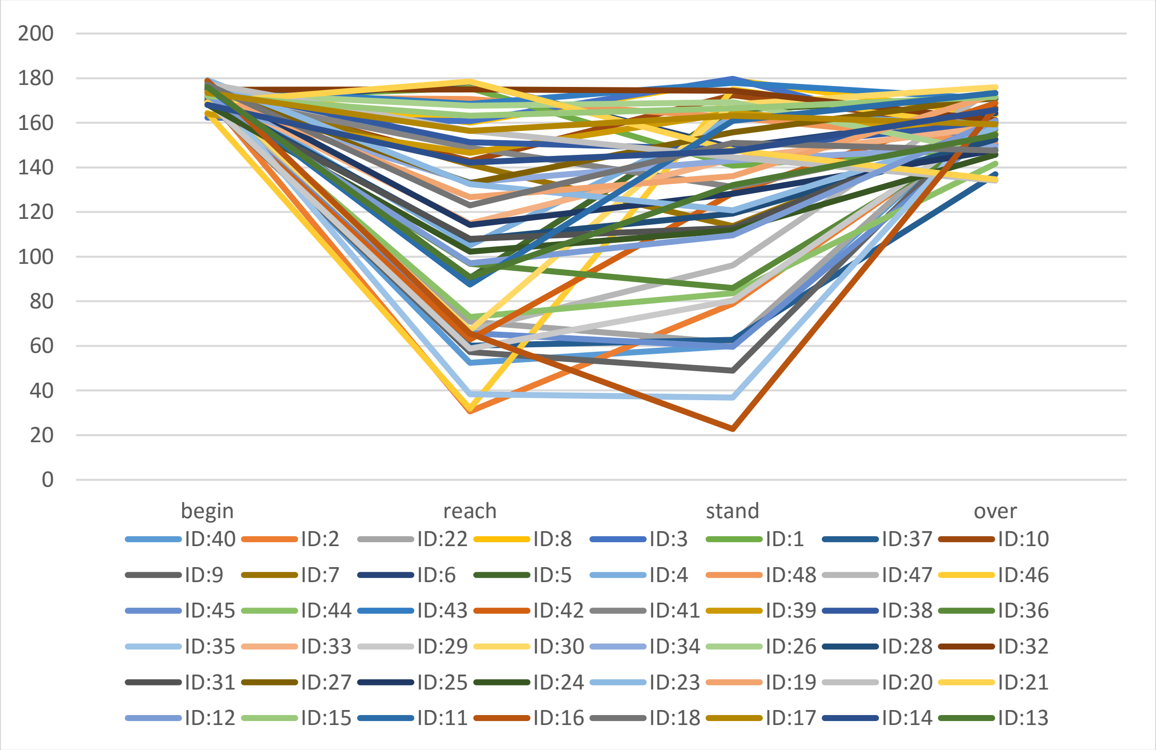


Figure 10. Right hip joint angles pattern (sample).

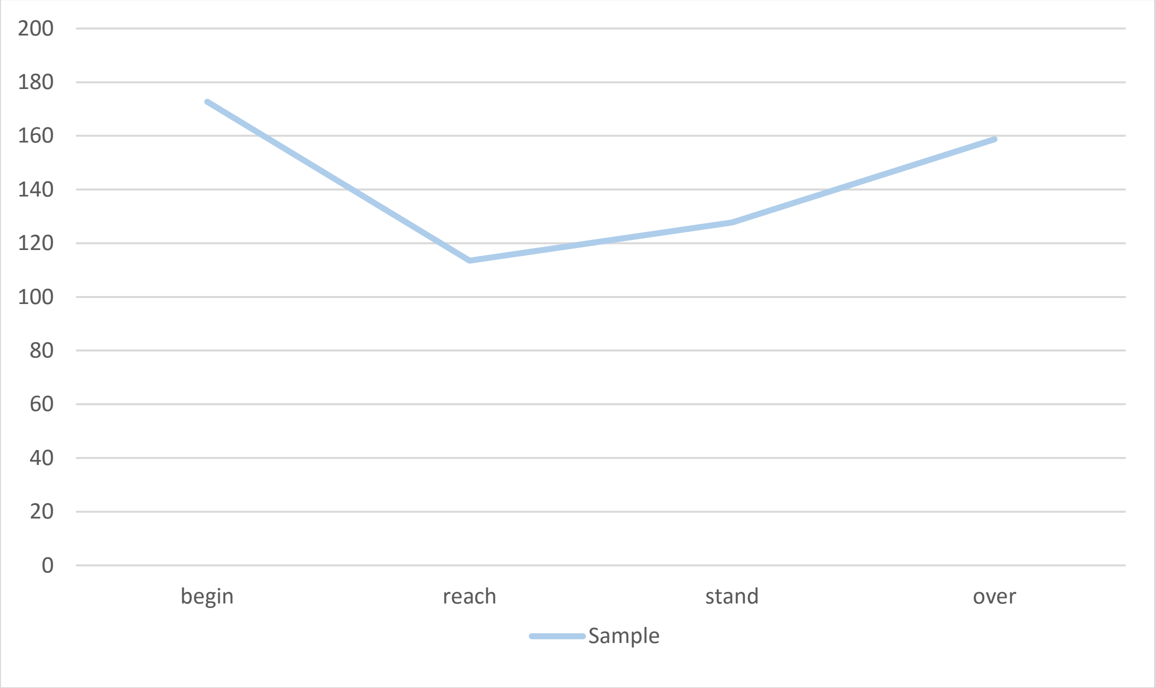


Figure 11. Right hip joint displacement pattern (individuals).

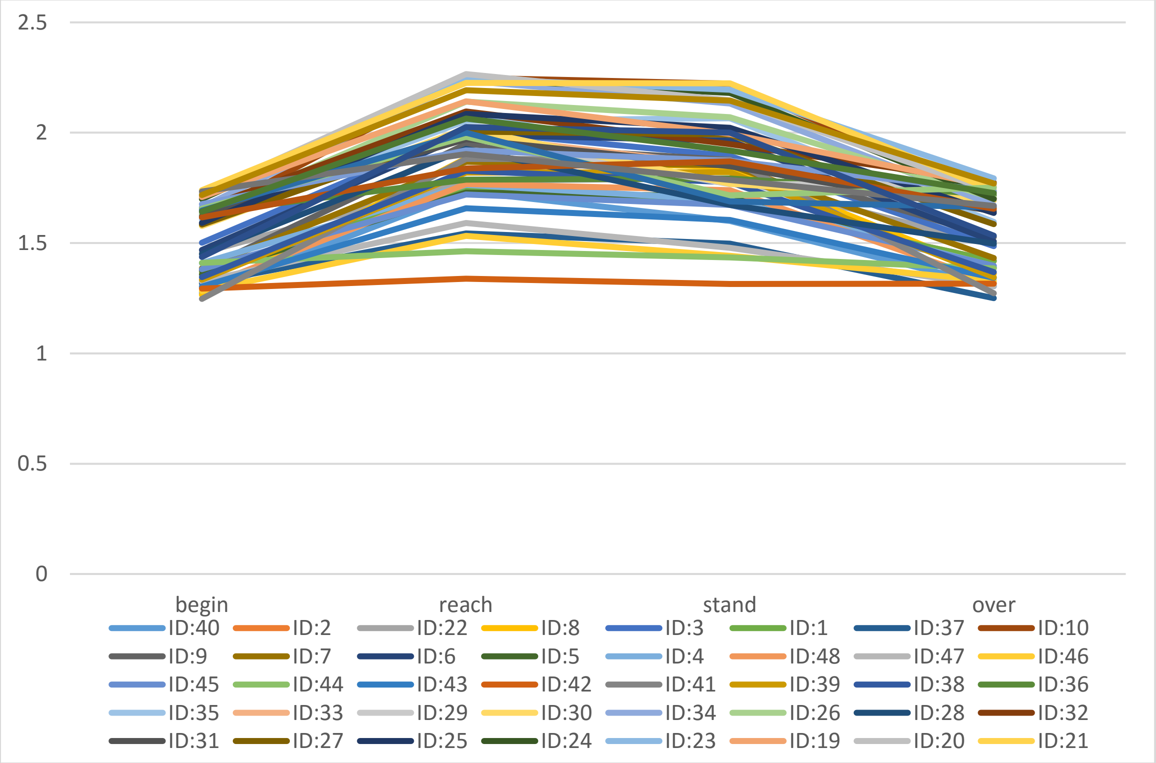


Figure 12. Right hip joint displacement pattern (sample).

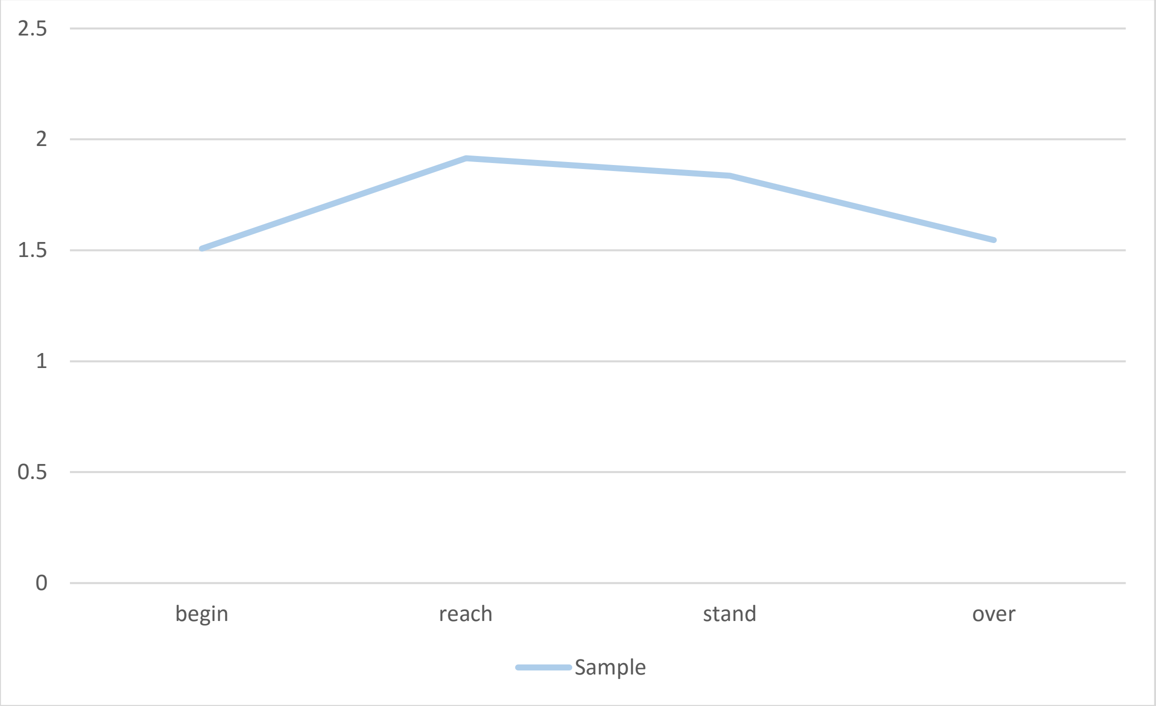


Table 3. Multiple regression of left lower extremity kinematics.

Unstandardized vs Standardized by Height	Beta value	95% Confidence Interval	T-value (p-value)	Unstandardized Standardized by Height
Knee Arc of motion (degree)	0.34 0.18	0.26~0.42 0.13~0.22	8.78* 7.99*	Y=0.34*knee-0.07*hip+22.65 R-squared=0.66 Shrinkage=0.09
Hip Arc of motion (degree)	-0.07 -0.04	-0.18~0.03 -0.09~0.02	1.43(p=0.16) 1.23(p=0.23)	Y=0.18*knee-0.04*hip+13.36 R-squared=0.62 Shrinkage=0.10
Constant value	22.65 13.36	8.44~36.87 5.23~21.48	3.21* 3.31*	

All assumptions of multiple linear regression were met.
"*" indicated the significant correlated relationship. ($p<0.05$).

Table 4. Multiple regression of left lower extremity kinematics with individual factors.

Unstandardized vs Standardized by Height	Beta value	95% Confidence Interval	T-value (p-value)	Unstandardized Standardized by Height
Knee Arc of motion (degree)	0.35 0.18	0.27~0.43 0.14~0.23	8.94* 8.43*	Y=0.35*knee-0.08*hip-0.11*weight+33.13 R-squared=0.68 Shrinkage=0.14 Remove id=14, 24, 47 R-squared=0.79 after diagnostic
Hip Arc of motion (degree)	-0.08 -0.04	-0.19~0.02 -0.10~0.01	1.63(p=0.11) -1.53(p=0.13)	
Weight (kg)	-0.11 -0.09	-0.27~0.06 -0.18~0.004	-1.32(p=0.20) -2.16(p=0.04)	Y=0.18*knee-0.04*hip-0.09*weight+21.98 R-squared=0.65 Shrinkage=0.15 Remove id=8, 24, 47 R-squared=0.77 after diagnostic
Constant value	33.13 21.98	11.76~54.51 10.01~33.94	3.12* 3.70*	

All assumptions of multiple linear regression were met.
"*" indicated the significant correlated relationship. (p<0.05

Table 5. Multiple regression of right lower extremity kinematics.

Unstandardized vs Standardized by Height	Beta value	95% Confidence Interval	T-value (p-value)	Unstandardized Standardized by Height
Knee Arc of motion (degree)	0.14 0.09	0.02~0.27 0.02~0.15	2.33* 2.67*	Y=0.14*knee-0.14*hip+44.99 R-squared=0.39 Shrinkage=0.18
Hip Arc of motion (degree)	-0.14 -0.08	-0.25~-0.04 -0.13~-0.02	-2.77* -2.88*	Y=0.09*knee-0.08*hip+24.48 R-squared=0.41 Shrinkage=0.12
Constant value	44.99 24.48	27.26~62.72 14.89~34.06	5.11* 5.08*	

All assumptions of multiple linear regression were met.
"*" indicated the significant correlated relationship. (p<0.05).

Table 6. Multiple regression of right lower extremity kinematics with individual factors.

Unstandardized vs Standardized by Height	Beta value	95% Confidence Interval	T-value (p-value)	Unstandardized Standardized by Height
Knee Arc of motion (degree)	0.12 0.07	-0.001~0.24 0.007~0.14	1.99(p=0.05) 2.23*	Y=0.12*knee-0.16*hip+0.35*Age+33.49 R-squared=0.43 Remove id=14, 35,42, 44 R-square=0.54 after diagnostic Shrinkage=0.33
Hip Arc of motion (degree)	-0.16 -0.10	-0.27~-0.06 -0.15~-0.04	-3.17 -3.44*	
Age (years)	0.35 0.23	-0.03~0.74 0.02~0.45	1.85(p=0.07) 2.22*	Y=0.07*knee-0.10*hip+0.23*Age+16.95 R-squared=0.49 Shrinkage=0.26 Remove id=28, 35,42, 44 R-square=0.59 after diagnostic
Constant value	33.49 16.95	12.16~54.83 5.50~28.40	3.17* 2.99*	

All assumptions of multiple linear regression were met.
"*" indicated the significant correlated relationship. (p<0.05).

Table 7. Correlation amongst variables

Correlation	Hip Vertical Displacement		Hip Vertical Displacement Standardized by Height	
	Frontal frame	Sagittal frame	Frontal frame	Sagittal frame
Knee joint angle arc of motion	0.81*	0.54*	0.78*	0.57*
Hip joint angle arc of motion	-0.30*	-0.56*	-0.27	-0.58*
Weight	-0.05	0.22	-0.04	0.14
Age	-0.03	0.19	-0.02	0.23
Weight Control for arc of motion	-0.20	0.15	-0.31*	0.05

“*” indicated the significant correlated relationship. ($p<0.05$).

Supplementary Figure

Figure 1

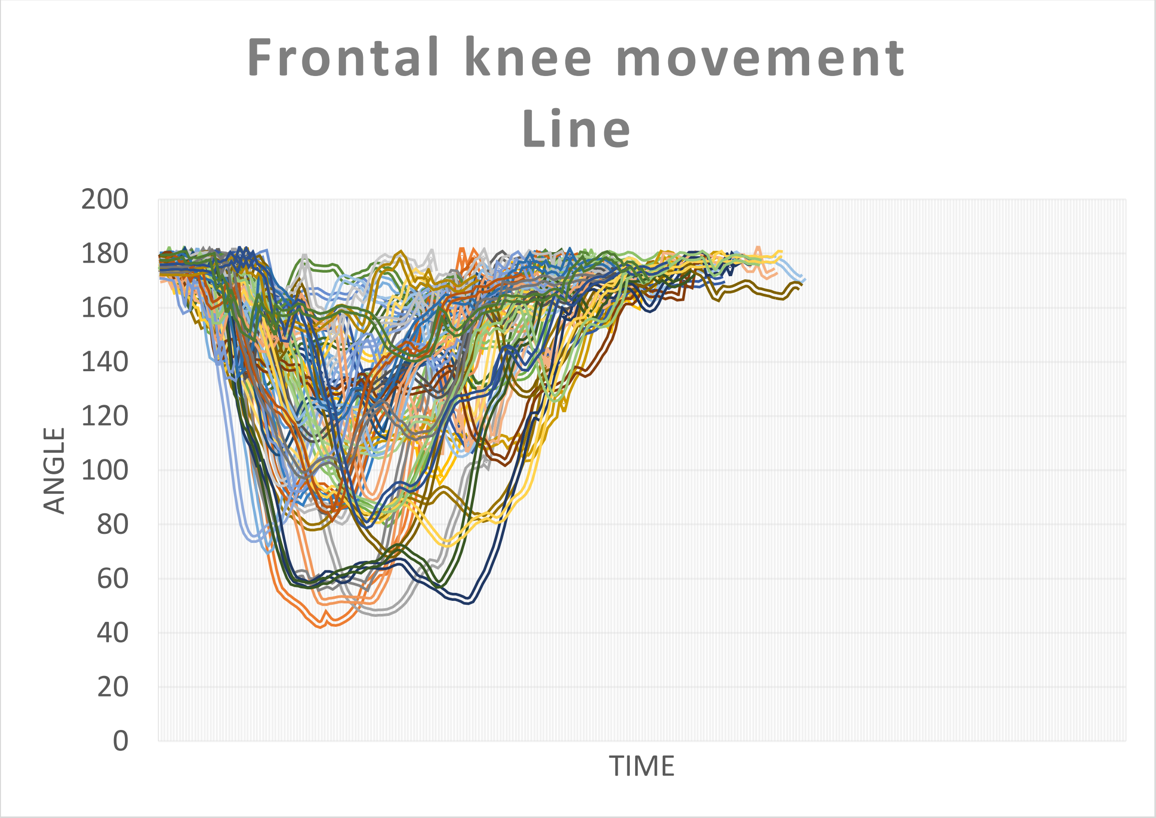


Figure2

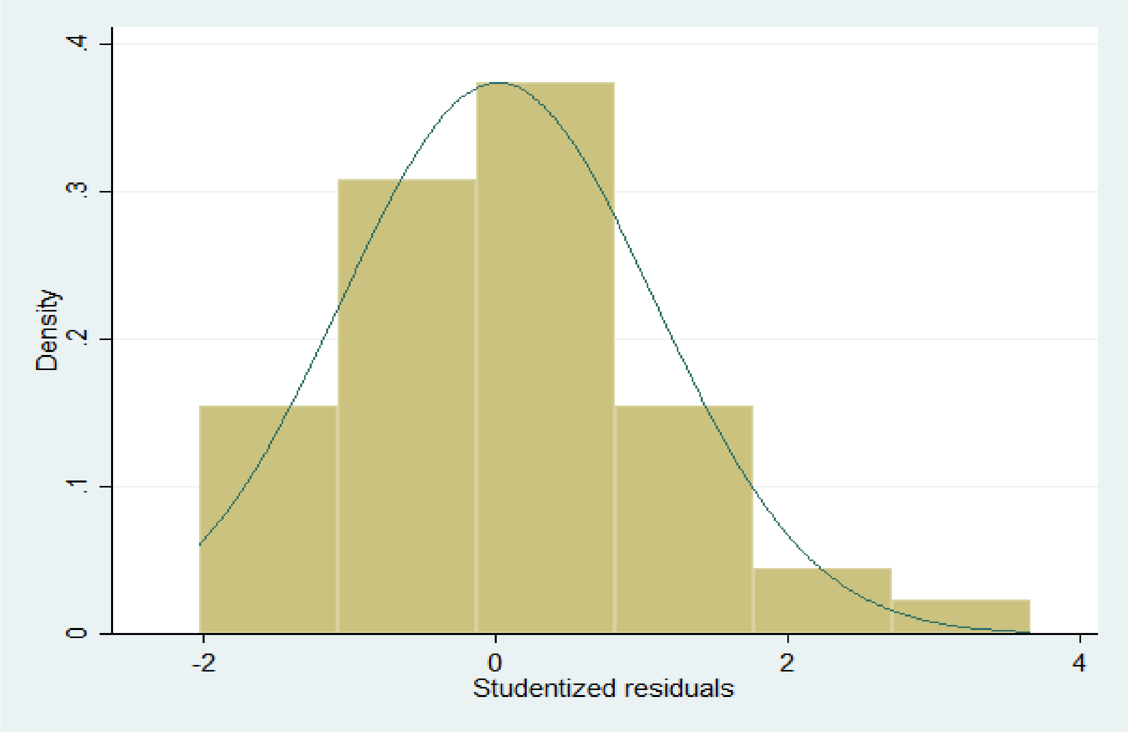
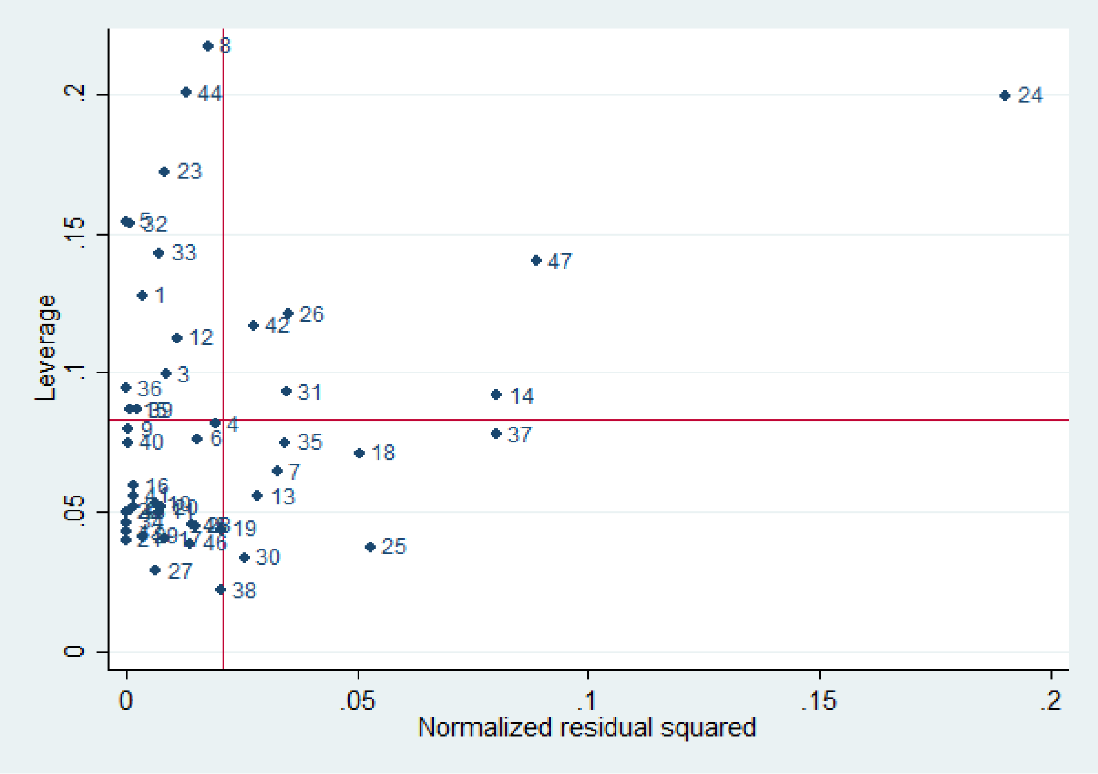


Figure3



CHAPTER 4: DISCUSSION/CONCLUDING REMARKS

This sandwich thesis focused on the utilizing the 2D movement analysis software in the context of firefighter task. The systematic review conducted for this thesis work demonstrated that Dartfish can be used as a reliable and valid measurement. The second study characterized lower extremity postures and hip vertical displacement during occupational fire-fighting task by Dartfish and established regression models. This work showed that body indicator and angle arc of motion contributes to hip joint displacement significantly.

The systematic review identified 22 studies in terms of the measurement properties of Dartfish. These papers were scored as good to excellence quality and supported substantial evidence to demonstrate Dartfish is a reliable and valid measurement with acceptable accuracy for measuring simple sit and reach test to mechanical lifting task. Appropriate camera setting, movement standardization and normalized kinematic information extraction procedure, reported results of the related study should be treated with confidence. However, the relatively small sample size or restricted age range of the participants would influence the generalizability of study outcome. Limiting recruitment to only males or females and perspective error would be reasons of inconsistence between the validity and reliability using Dartfish. With the comparison of X-ray and goniometric, Dartfish shows the interchangeable quality for quantifying the static distance and angle. In the context of dynamic motions, this should be applied carefully for the multi-planar movements. The factors caused the issue of reliability for using Dartfish on measuring static kinematic information are different from the perspective error for dynamic motions.

Therefore, professional experience, subjective judgement and various participant motion performance has a significant influence of using Dartfish.

The purpose of the second study was to apply 2D movement analysis software to identify firefighters' trunk and knee postures during a firefighting lift task while wearing PPE and to subsequently model multiple linear regression relationships among the kinematic variables generated. Lower extremity postures and hip vertical displacement during occupational fire-fighting task has been characterized followed the data extraction procedure in previous research. Study findings suggested that firefighters required from 83.90° to 96.27° of both left and right knee range-of-motion during the completion of lift task. With the consideration of preventing possible work-related injuries, this outcome provided the basic, task-based, range-of-motion guidelines. The result of regression analysis suggested that firefighters moved almost one fourth of body height (24.52% of height) to lift the HRP from floor to the shoulder level. Through the stepwise selection, weight has been included as an independent variable for left lower extremity and age for right extremity. Nearly 25% of the R-square difference (0.68-0.43) also support the conclusion that right side lower extremity extracted from sagittal frame was relatively inaccurate comparing with the left lower extremity extracted from the frontal camera due to the perspective error. Based on the systematic review in the current thesis, although the distance between optical axis and body segment has been maximized, rotational angle still existed in data extraction procedure. However, through the regression model established in this thesis, the lack of accuracy using angle tracking to record multi-planar movements could be reduced. Moreover, our model all enhance the clinical application of hip vertical displacement.

There are serval limitations in this study. Firstly, for both manuscripts, only studies published in English were included. Further, in terms of the systematic review, only one movement analysis software, Dartfish, has been focused. Another important limitation of this research is the relatively small sample size based on sample size calculation. This could result in an insufficient power to identify potential predictors. Bootstrap sampling has been conducted to test the internal-validation and indicated a generalizability issue existing in the regression model for left-side lower extremity postures. However, comparing with previous studies in similar research field, current study shows substantial improvement.
Due to the cross-sectional study design, our regression could not be interpreted as causation, but as association. That is to say, increased arc of motion of knee joint angle, decreased arc of motion of hip joint angle are positively associated with function. Lastly, a potential limitation of this study is referencing the stripe of the firefighter’s coat to standardize the placement of mark points during analyzing the performance of task. The unfixed spatial feature could influence the accuracy of measuring.

For future research, infrared camera could be introduced in the study. The attachable infrared emitting diodes seem to be another strategy to remedy the issue caused by virtual markers function in Dartfish. Efforts should be made to minimize the magnitude of perspective error. For example, add an overlook position camera and adjust the rotational angle equation could be an effective solution.

Our study has significant implication in the field of work-related injury prevention.

With the combined angle and displacement model, clinicians could help firefighters to formulate health tasks posture with the movement posture guideline. Furthermore, engineers could develop prevention plan of work-related musculoskeletal disorder for firefighters. For example, portable devices with the application of Computer-Human Interaction technology enables firefighters to acknowledge the real-time parameters in terms of physical demand and postures standards during applied task.

In conclusion, this study adds to the existing pool of evidence to understand the 2D motion analysis system in the occupational context. Our findings move towards development of injury prevention that informs the evaluation and rehabilitation in the firefighter applied context.