DYNAMIC BIOMECHANICAL SIMULATION FOR IDENTIFYING RISK FACTORS FOR WORK-RELATED MUSCULOSKELETAL DISORDERS DURING CONSTRUCTION TASKS

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ABSTRACT

We propose a dynamic biomechanical simulation method that uses motion capture to evaluate the risk of Work-related Musculoskeletal Disorders (WMSDs). Statistics show that WMSDs accounted for 33% of all non-fatal occupational injuries and illness in construction in 2009, and were a leading cause of temporary and permanent disability. Present methods rely largely on self-reports from workers, observational techniques, and direct measurements of motion and muscle activity to assess awkward postures, physical loads, repetitiveness, and the duration of exposure. While these methods have helped to prevent WMSDs in construction work, they may not be suitable for estimating the internal tissue loads associated with WMSDs. We propose a dynamic biomechanical simulation method to estimate internal forces and moments at each body joint of construction workers with motion capture data. Particularly, we explore the biomechanical loads by simulating active 3D musculoskeletal models based on measured postures and movements. To demonstrate the feasibility of this approach, we studied a ladder climbing task using a portable ladder under controlled laboratory conditions. Postures and motions were determined with a commercial motion capture system (e.g., VICON). The results were analyzed to investigate the feasibility of identifying risk factors based on biomechanical simulation. The results show that the proposed approach allows us to determine the biomechanical basis for WMSDs, and to identify postures and movements associated with excessive physical demands on each body joint. When combined with marker-less motion capture which is our ongoing work, the proposed approach has the potential to assess an individual's motions and to provide personalized feedback for the purpose of reducing biomechanical loads and WMSD risk in real workplaces.

KEYWORDS

Work-related musculoskeletal disorders, Biomechanical model, Motion capture

INTRODUCTION

In the labor-intensive construction industry, workers are frequently exposed to manual handling tasks involving forceful exertion and awkward postures. As a result, construction workers are at about a 50 percent higher risk of work-related musculoskeletal disorders (WMSDs) than workers in other industries (Schneider, 2001). Musculoskeletal disorders in construction not only cause construction workers to face a loss of earnings by being unable to work, but also result in significant cost to construction companies due to productivity loss, sickness absenteeism, or ill-health retirement (Valsangkar & Surendranath, 2012).

Previous research efforts to prevent work-related musculoskeletal disorders in construction have focused on identifying awkward postures that may contribute to the development of WMSDs. Alwasel et al. (2011) applied magneto-resistive sensors to measure body joint angles, and identified workers' exposure to unsafe postures during construction tasks. Ray & Teizer (2012) suggested real-time analysis on construction workers' posture using a Kinect range camera to detect non-ergonomic activities. Li and Lee (2011) introduced a computer-vision–based approach to obtain construction workers' motion data from video, and identified unsafe postures and movements to prevent WMSDs by giving feedback to the workers. However, a precipitation of WMSDs is an interactive process of biomechanical and physiological internal responses of the human body to external physical stresses (e.g., posture, exertion, and vibration) during occupational tasks (Kumar, 2001). In particular, the level, duration, and frequency of the loads imposed on tissues are critical factors in determining whether WMSDs occur (Armstrong et al., 1996). Though the posture-based approaches previously used to assess the risks of WMSDs in construction have provided valuable insights into preventing WMSDs, these methods may not be suitable for assessing the internal loads on the human body during construction activities.

To address these issues, we propose a marker-less motion capture approach for on-site (i.e., field) musculoskeletal stress analysis during construction tasks in real sites (Figure 1). Specifically, the proposed approach captures workers' motion data from ordinary video or network surveillance cameras (Li & Lee, 2011; Han et al., 2012b; Han et al., 2013) and an RGB-D sensor (e.g., KINECT sensor) (Han et al., 2012a; Han & Lee, 2012). Then, the approach assesses risk factors that can produce excessive physical loads on the human body through a biomechanical analysis using motion data collected from various real-world conditions.

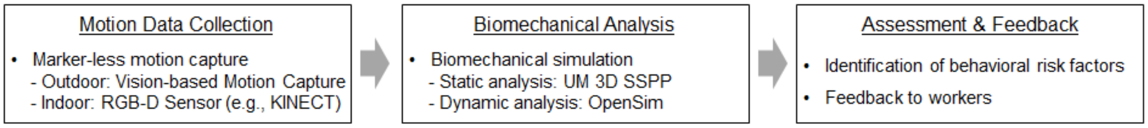


Figure 1 – Marker-less motion capture approach for on-site musculoskeletal stress analysis during construction tasks

In this paper, as a preliminary study of the proposed approach, we explore why it is necessary to quantify musculoskeletal stresses exerted on the human body as a response to external physical factors such as awkward postures and forceful exertions, and how the musculoskeletal loads are estimated based on motion data that is collected from construction sites. The literature was analyzed to address the biomechanical and physiological mechanisms of WMSDs, and to describe previous research efforts to assess the risk of WMSDs.

Then, we examine the feasibility of a dynamic biomechanical simulation based on motion data to estimate musculoskeletal stresses on the human body from a case study on ladder climbing activities. For this case study, workers' motion data is collected using a marker-based motion capture system that is useful for capturing the accurate movement of whole body parts as a demonstration purpose of the feasibility of our approach. Based on the case study, we discuss a potential issue when a marker-less motion capture is applied for field-based biomechanical analysis instead of a marker-based approach presented in this paper. In addition, an area for improvement in biomechanical simulation is suggested.

RISK ASSESSMENT OF WORK-RELATED MUSCULOSKELETAL DISORDER

Biomechanical and Physiological Mechanisms of WMSDs

Work-related musculoskeletal disorders (WMSDs) is a term that refers to abnormalities in the soft tissues associated with the bones and joints in the human body during occupational tasks (Aptel et al., 2002). The most common diagnoses of WMSDs are carpal tunnel syndrome, tendinitis, and back pain (OSHA 1999), and develop over time due to repeated overuse and insufficient recovery, which means that corrective actions—identifying and eliminating any risks of WMSDs—should be taken before the symptoms get worse (Simoneau et al., 1996). The primary prevention of WMSDs can be achieved by reducing exposure to risk factors (Armstrong et al. 1996) that may produce excessive physical stresses acting on the body beyond a human capacity (Radwin et al., 2001).

Previous research efforts have identified mechanisms for WMSDs to describe various factors that may play in the development of musculoskeletal disorders, and to address biomechanical aspects and interactions between those factors. Armstrong et al. (1996) presented a conceptual model for the development process of WMSDs based on the collective experiences of researchers. The distinguishing feature of the model is that WMSDs are considered to be a result of complex interrelationships between these four sets of variables: 1) exposure, 2) dose, 3) capacity, and 4) response. For example, exposure to the external factors (e.g., awkward postures and forceful exertion) at workplaces produces the internal doses referring to musculoskeletal stresses and metabolic demands. When responses to these doses exceed the human capacity, a musculoskeletal disorder occurs.

Kumar (2001) also suggested a multivariate interaction theory describing that a precipitation of WMSDs is an interactive process between genetic, morphological, psychosocial, and biomechanical factors.

The underlying hypothesis of the theory is that the risk of WMSDs increases when a worker is exposed to excessive physical stresses beyond the worker's functional capacity. The stress level is determined by the biomechanical risk factors and types of work performed. All these factors change over time. For example, the capacity can be increased by physical training, or decreased by exposure to psychological stress.

Radwin et al (2001) also recognized the interrelatedness of risk factors causing WMSDs. He introduced a cumulative trauma load-tolerance model that describes a complex interaction of biomechanical events causing WMSDs (Figure 2). The model illustrates that external loads produced in the physical work environment are transmitted to the body through a biomechanical pathway. For example, the external loads—which are physical stresses such as force, motion, vibration, and temperature—create internal loads on tissues and anatomical structures. As a result of physiological responses, the internal loads produce mechanical strain and fatigue that may result in pain, discomfort, and even musculoskeletal disorders. By emphasizing the interactive relationships between risk factors, the models discussed above suggested the necessity of quantifying exposure to these factors to reduce WMSDs in workplaces.

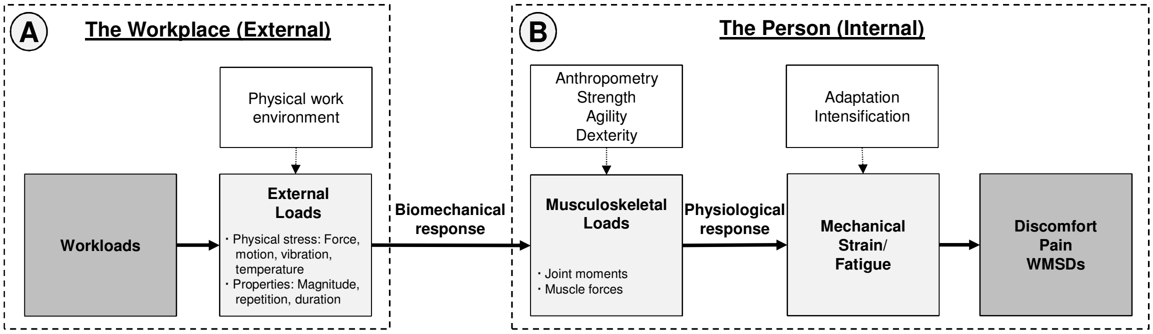


Figure 2 – A cumulative trauma load-tolerance model (adapted from Radwin et al. (2001))

Assessment methods of WMSDs

Previously, a wide range of methods for the risk assessment of WMSDs has been developed and categorized into: 1) self-reports (e.g., interviews and questionnaires), 2) observational methods, and 3) direct measurements (e.g., sensors) (Li & Buckle, 1999; David, 2005). Self-reports from workers can be used to collect data on exposure to both physical and psychosocial factors through worker diaries, interviews, and questionnaires (David 2005). Observational methods concentrate on working postures and movements during occupational tasks (Buckle 1999). To describe body postures directly, electric instrumental methods—such as the goniometric system, the optical scanning system, the sonic system, the electromagnetic system, and accelerometer-based systems—have been developed (David 2005).

However, these techniques focused on exposure to external risk factors (e.g., awkward postures, forceful exertion) (A in Figure 2) causing WMSDs, and may not be suitable for measuring and assessing the internal musculoskeletal stresses (B in Figure 2) required for manual works. To address this issue, biomechanical models of the human body have been widely used to understand and reduce the risk of WMSDs in the workplace (Marras & Radwin, 2005). Biomechanical models describing complex musculoskeletal systems of the human body (Bean et al. 1988) help to estimate internal forces that can rarely be measured directly (Chaffin et al. 1996). Based on the assumption that the actions of the human body follow the laws of Newtonian mechanics, the biomechanical models provide a quantitative assessment of the musculoskeletal loads during occupational tasks, which helps one to identify hazardous loading conditions on certain body parts (Marras & Radwin, 2005). Recently, several computerized simulation and analysis tools (e.g., 3D SSPP, OpenSim) based on three-dimensional biomechanical modeling have been developed for the ergonomic assessment of the risks of WMSDs, and provide both proactive and reactive analyses of work tasks.

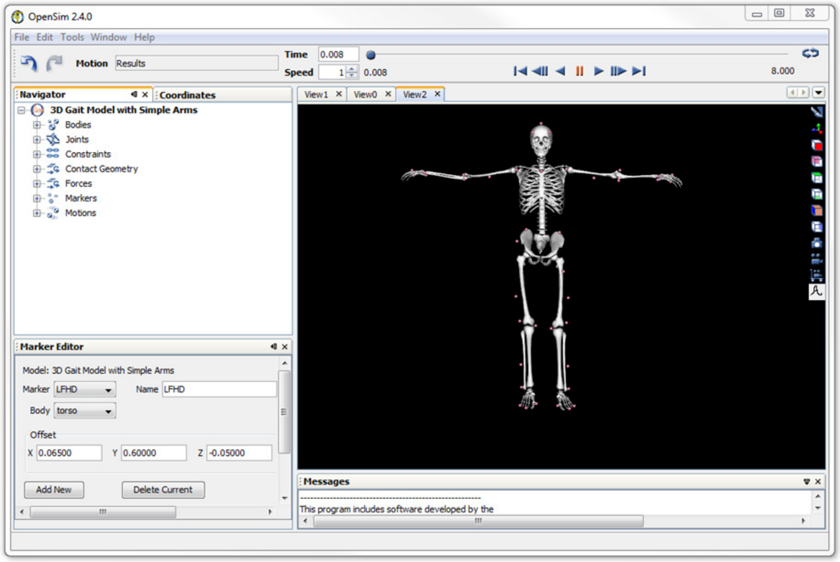
There have been significant research efforts focusing on measuring muscle fatigue that is produced by repetitive internal loads on the human body. Fatigue occurs when the exertions are sustained or when there is insufficient recovery time between successive exertions. One way to measure the fatigue level of workers is to investigate the discomfort caused by fatigue (Corlett & Bishop, 1976). This method assumes that the spatial and temporal discomfort patterns reflect the loads imposed on various parts of the body to perform a given activity or task. So, workers are asked to identify body parts with objectionable discomfort based on their memory of a typical or specific workday. Another method is the synchronous recording and computerized analysis of myoelectrical activity (EMG). This can be used evaluate local muscle fatigue that relies on changes in the spectral characteristics of the myoelectric signal, although the relationship may be non-linear in many circumstances (David, 2005). However, these methods are difficult to identify what factors exactly contribute to fatigue because they focused on symptoms of fatigue.

METHODS

Dynamic biomechanical simulation using OpenSim

This paper highlights the measurement of musculoskeletal stresses as a mean of assessing the risk of WMSDs. We explore an application of OpenSim (Delp et al., 2007) to estimate biomechanical stresses exerted on human body joints with the purpose of identifying behavioral risk factors during construction tasks. OpenSim, which is a freely available software package, is applied for dynamic biomechanical analysis. Given the motion and external force data, OpenSim performs inverse dynamics analysis with a multibody system that has rigid skeletal bones paired with muscles to calculate joint moments from joint angles and external forces (Symeonidis et al. 2010).

Given the kinematics of human motion, inverse dynamics quantitatively estimates the internal loads (joint reaction forces and moments) acting on the bones and joints of the human body by using a biomechanical model (Risher et al., 1997). OpenSim simulates the model to solve the equations for inverse dynamics with external forces (e.g., ground reactions forces) and motion data defined by the generalized positions, velocities, and accelerations (SimTK 2012). OpenSim can import motion data that is collected from experiments using motion capture systems. The procedure for the simulation in OpenSim is as follows (SimTK, 2012).



Motion Results
Time 0.008
Speed 1 0.008
8.000

Model: 3D Gait Model with Simple Arms
Marker LFHD Name LFHD
Body torso
Offset
X 0.06500 Y 0.60000 Z -0.05000

This program includes software developed by the

Figure 3 – OpenSim window and a musculoskeletal model.

Scaling a model

The purpose of scaling a model is to modify the anthropometry or physical dimensions of the musculoskeletal model to match it with the subject's anthropometry using the kinematics obtained from the motion capture system. From the scaling, OpenSim adjusts both the mass properties (mass and inertia) and the dimensions of the body segment.

Inverse kinematics

Inverse kinematics is the process used to calculate coordinate values (joint angles and translations) for the model from the motion data. By matching the model's virtual marker locations from the motion capture system with the measured marker locations to minimize the geometrical differences between them, generalized joint angles are determined.

Inverse dynamics

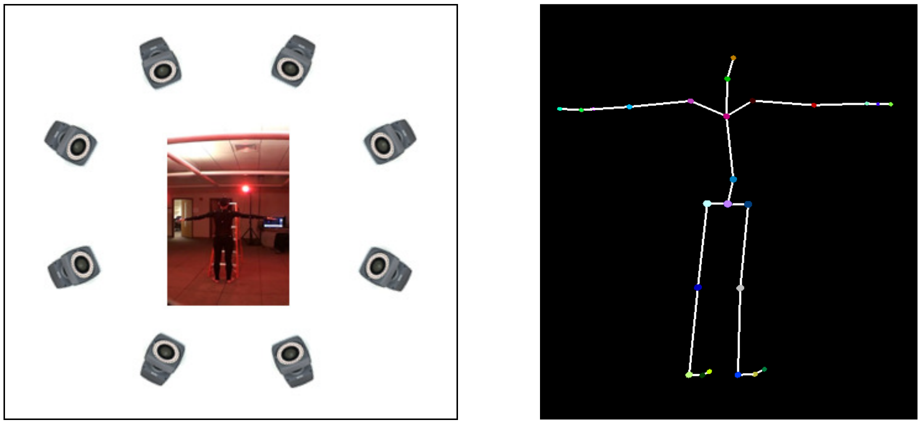
Inverse dynamics determines the net forces and torques at each joint that produces movement by solving the equations of motion with the given motion data (joint angles from inverse kinematics) and external force data. The external forces (e.g., ground reaction forces) that are obtained from experiments can be applied to the model.

Data collection for case study

To test the feasibility of the estimation of musculoskeletal stresses using OpenSim during construction tasks, we performed the biomechanical analysis with motion data from the VICON system—a commercial marker-based motion tracking system (http://vicon.com). The VICON captures the movement of an object with multiple cameras by tracking reflective markers attached to a human body (i.e., joints) (Figure 4(a)).

As a testing task, we selected ladder climbing activities that have a high risk of localized fatigue and WMSDs due to forceful exertion on hands and feet (Kumar, 1999). The male subject whose height was 72 inches, and weight was 175 lbs ascended and descended a portable ladder, and each action was repeated 25 times. In total, the VICON produced 12,909 frames with the frame rate of 120 frames per second. From the VICON, two different types of motion data were obtained (.trc and .bvh file formats). The motion data in the .trc file format, which specifies the positions of markers placed on a subject at different times during a motion capture trial, was used for the processes of scaling and inverse kinematics in OpenSim. The motion data in the .bvh file format was collected to analyze the subject's movement (Figure 4(b)).

External force data—ground reaction forces during ladder climbing—were determined from the subject's weight. From the laboratory experiments, Armstrong et al. (2008) found that the average peak resultant foot forces are 94%–100% of the subject's bodyweight when s/he is moving one foot to the next rung, and the weight is distributed across both feet if both feet are on a rung. Based on this finding, we assumed that if one foot is in the air, the other foot supports 100% of the bodyweight. Also, when both feet contact a ladder or the ground, it is assumed that the ground reaction forces on each foot are half of the subject's bodyweight.



(a) Camera configurations (b) Motion data from VICON

Figure 4 – Camera configurations of VICON (a) and 3D skeleton of motion data (b)

RESUTLS

Joint moments in ankles during ladder climbing

This research performed a dynamic biomechanical simulation in OpenSim with the motion data from the VICON. During ladder climbing activities, there exists the potential for localized fatigue at the elbow, hip, and ankle joints due to forceful and repetitive exertion (Bloswick & Chaffine, 1990). In this paper, we analyzed biomechanical simulation results focusing on ankle moments.

Figure 5 shows joint moments (lb-in) in ankles during one cycle of ladder climbing (ascending and descending). The joint moments (lb-in) in ankles range from 600 lb-in to 2,200 lb-in, and the average of moments is 1250 lb-in. In the previous research on work load during ladder climbing (Hoozemans et al., 2005), the maximum total moments in ankles from five tall subjects range from 900 lb-in to 1,300 lb-in when accelerations of body segments are not considered. It is presumed that the deviations between ankle moments from the previous research and those in our research result from inertial forces and different experimental conditions such as ladder slant.

In addition, the moments produced at ankles show relatively constant values when the feet are on a rung. In the biomechanical models applied in OpenSim, the ground reaction forces are dominant variables to determine ankle moments. As mentioned above, we assumed that the ground reaction force is the constant value of 100% of the bodyweight. Since the foot forces change (increase, stabilize, and decrease) under real conditions (Armstrong et al., 2008), we expect that the ankle moments show similar patterns as patterns of foot forces if we apply actual foot forces measured from experiments.

In dynamic situations where accelerations exist during movements, the moment at each body joint is the sum of the static moment and the moments produced by the dynamic inertial effect (Chaffin et al. 2006). As shown in the moment graph in Figure 5, the moments at ankles increase as the subject climbs a ladder due to the acceleration effect, even though the climbing style is not changed (The time interval when the force is exerted in ankles gets shorter as the subject climbs a ladder, which means that the climbing speed gets faster, resulting in the acceleration.).

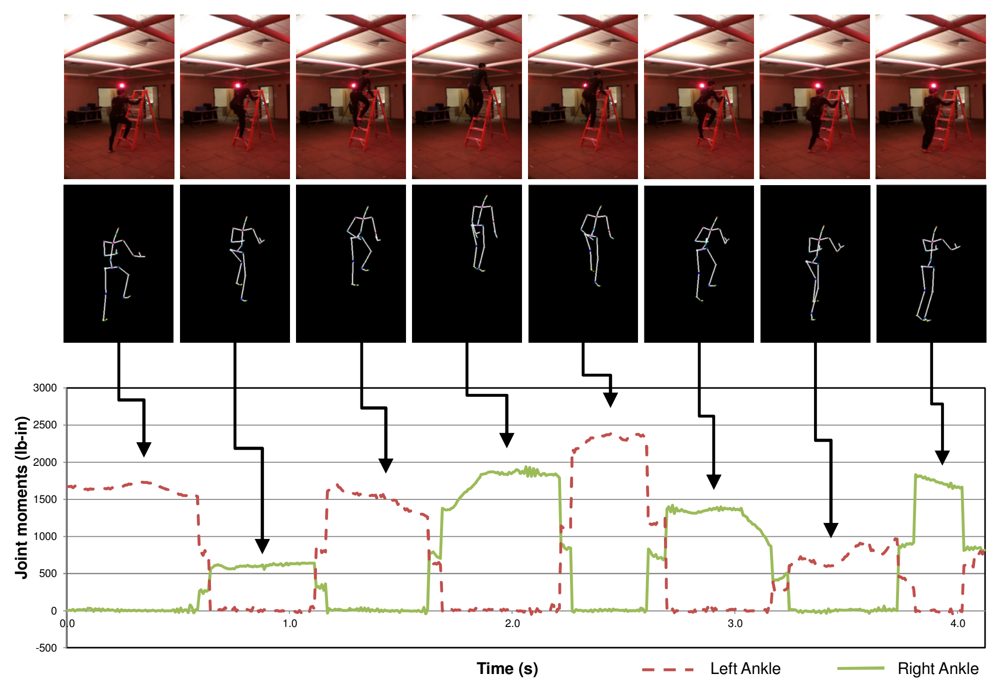


Figure 5 – The result of biomechanical analysis during ladder climbing

Discussion for biomechanical simulation using marker-less motion capture under real conditions

A biomechanical simulation using OpenSim provides a quantitative assessment of behavioral risks based on postures and movements during construction tasks. The magnitude, duration, and repetition of the musculoskeletal loads exerted on the human body are fundamental factors that cause WMSDs (Kilbom et al., 1996). Thus, the quantitative measurement of joint moments exerted on body joints is critical in identifying the risks of these disorders. The proposed approach has great potential as a field-oriented ergonomic evaluation method, illustrating how biomechanical analysis based on workers' postural information can be achieved during construction tasks.

Despite its benefit, there are several issues to be addressed for an application of OpenSim using motion data from a maker-less motion capture. First, motion data collected from a marker-based and a maker-less motion capture has different configurations. While a marker-based system such as VICON provides information on both marker positions and body postures, only postural information can be obtained from a maker-less motion capture (Han et al., 2012a; Han & Lee, 2012). However, OpenSim is designed to conduct a biomechanical simulation with experimental data, such as marker positions and kinematics obtained from marker-based motion capture systems, which is an obstacle for applying a marker-less motion capture. Especially, in OpenSim, the motion data with geometrical information on markers are necessary for the scaling and inverse kinematics processes to calculate joint angles. In order to apply motion data from the proposed marker-less motion capture, we need to calculate the joint angles without the scaling and inverse kinematics processes, and then import the angular data of body joints into OpenSim, so as to enable OpenSim to conduct inverse dynamics. In addition, OpenSim does not provide allowable strength limits on each body joint. When a worker performs a certain task, the moments created at each joint must not exceed the muscular moment strengths at each joint (Chaffin et al. 2006). For this reason, the acceptable internal loading conditions have to be determined to assess estimated musculoskeletal stresses from OpenSim.

To address the first issue described above, as future research, we will test an alternative method to calculate joint angles from marker-less motion capture. The motion data format (e.g., BVH file format) extracted from the marker-less motion capture expresses sequential postures with rotation angles. This format defines the hierarchical and spatial structure of a human body and stores a 3D position of a root body joint (e.g., a hip); thus, 3D positions of all of the body joints can iteratively be computed from the root joint using translations and rotations (i.e., a transformation matrix). Using the 3D locations (x,y,z coordinates) of body joints that are calculated from the motion data in the BVH file format, the joint angles that are required for inverse dynamics in Opensim can be computed based on the vectors of bones in a local coordinate system of the body. In addition, these processes require a series of post-processing of motion data for use with Opensim, which is an obstacle for field-based analysis in real time. In order to enable real-time analysis, we will also compile the code for data processing in OpenSim which allows customized controls of its functions.

For the second issue, we will investigate maximum allowable joint moments in body joints under dynamic conditions from previous research efforts. There have been tremendous research efforts to figure out allowable internal loading conditions and population strengths that can be used as a threshold to determine whether internal forces produced by external physical loads are acceptable or not. For example, NIOSH (1981) suggested a recommended weight limit for lifting tasks under static situations, and then developed the Lifting Index that defines the level of physical stress; thus unsafe postures can be identified.

CONCLUSIONS

We propose a dynamic biomechanical simulation for on-site musculoskeletal stress analysis during construction tasks in real sites. To do so, this paper highlighted the feasibility of the biomechanical analysis tool, OpenSim and performed a case study on ladder climbing activities using motion data from VICON. Ankle moments from the dynamic biomechanical simulation using OpenSim were analyzed and compared with ankle moments that were derived from the previous research efforts in laboratory experiments. The results showed that the proposed tool has a great potential to quantitatively assess workers' behavior in terms of internal loading conditions, illustrating how biomechanical analysis based on workers' motion data can be achieved during construction tasks.

In addition, we identified two potential issues that arise when the biomechanical simulation in OpenSim is applied under real conditions: 1) applying motion data from marker-less motion capture approaches that don't have information on marker positions, and 2) determining allowable strength limits to assess ergonomic risks due to musculoskeletal stresses during construction tasks. In our future research, computational methods to combine marker-less motion capture with biomechanical analysis tools (e.g., OpenSim) will be developed, and allowable internal loading conditions will be investigated.

Quantifying biomechanical stresses helps to understanding behavioral risks during construction tasks. Further, the continuous behavior monitoring of biomechanical stresses will provide effective ergonomic interventions (e.g., feedback to workers on their postures), thereby contributing to the prevention of work-related musculoskeletal disorders.

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