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RESEARCH ARTICLE

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Motion-based analysis for construction workers using biomechanical methods

Abstract Sustaining awkward postures and overexertion are common factors in construction industry that result in work-related injuries of workers. To address there safety and health issues, conventional observational methods on the external causes are tedious and subjective, while the direct measurement on the internal causes is intrusive leading to productivity reduction. Therefore, it is essential to construct an effective approach that maps the external and internal causes to realize the non-intrusive identification of safety and health risks. This research proposes a theoretical method to analyze the postures tracked by videos with biomechanical models. Through the biomechanical skeleton representation of human body, the workload and joint torques are rapidly and accurately evaluated based on the rotation angles of joints. The method is then demonstrated by two case studies about (1) plastering and (2) carrying. The experiment results illustrate the changing intramuscular torques across the construction activities in essence, validating the proposed approach to be effective in theory.

Keywords biomechanical method, motion-based analysis, construction worker, muscular torques, workload

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1 Introduction

Construction assignments on sites are energy consuming and greatly depend on the manual handling of labor crew. Since such tasks are generally repetitive and sustained application of force or sustained awkward postures, construction workers frequently suffer from workplace injuries such as work-related musculoskeletal disorders (WMSDs), incapacity for work or death (Martínez-Rojas et al., 2016; Pinto et al., 2011). Occupational Safety and Health Statistics revealed that construction industry accounted for 17% of occupational injuries among all industry sections in 2015 (Occupational Safety and Health Branch Labour Department, 2016). Therefore, the safety and health (S&H) issues become foreland research fields in both industry and academia. Various state-of-the-art technologies, such as wearable devices and computer vision, have been applied to track the process of construction tasks to facilitate the assessment of the potential safety and health risks for construction workers. However, taking the human physiology, such as muscular system into account for the motion-based analysis is still an open challenge, which facilitates further analysis on construction motions in a holistic and essential manner and provides the foundation for the simulation of construction accidents.

Biomechanics is a popular theory applied to assess the safety and health risks in kinematics, rehabilitation, etc. Based on the physiological structure and mechanical properties of human body, biomechanics uses the laws of mechanics to analyze the formation, dynamics and balance of postures. Compared with the conventional approaches relying on self-evaluation, such as interviews and questionnaires, biomechanical models are more objective approaches to provide an accurate assessment and enable prediction of construction motions. Using biomechanics in kinematical motion analysis, scholars gained deep insights on the mechanism of sports motions, and then athletes improved the sports performance as well as reduced the safety risks accordingly. This study aims to propose a novel approach to analyze the construction motions based on mechanical models, providing a reliable evaluation to predict the effects of construction activities on the safety and health of construction workers. Such evaluation enables superintendents to optimize the personnel protective equipment and improve the productivity performance at the view of construction motions.

2 Background

The root causes of construction unsafe and unhealthy motions can be divided into: (1) The external causes, such as awkward postures and forceful exertions, and (2) the internal causes, such as elevated intramuscular strains and torques as well as the fatigue of muscles and inflammations of tendons.

External causes have drawn the attention of academia and industry for decades. Most of the earlier studies measured external causes in manual methods. For example, Buchholz et al. (1996) invented PATH (Posture, Activity, Tools and Handling) as the assessment standard of hazardous postures. Golabchi et al. (2016) also applied an observation method to assess the effects of various postures on human body based on Rapid Upper Limb Assessment (RULA). Hartmann and Fleischer, 2005 applied observation to study posture constraints. In addition, Takala reviewed the observational methods to assess the body postures and workloads systematically (Takala et al., 2010). However, the subjective assessment based on observation is time- and labor-consuming with low repeatability among different observers (Takala et al., 2010). With the development of sensor technology, Inertial Measurement Units (IMU) have been used to solve the above problem (Yan et al., 2017; Umer et al, 2017). IMU measures the relative rotation angles of joints, and human body postures can be computed based on these joint parameters. The method is automatic and objective, so it can ‘observe’ worker’s postures accurately in a time- and labor-saving way. The disadvantage of the method lies in its intrusiveness, which means that workers have to be equipped with various sensors at or around their joints, resulting in potential negative impacts on normal construction operation. To address the issue, many studies have utilized computer vision to solve the problem (Ray and Teizer, 2012; Gong and Caldas, 2011; Peddi et al., 2009; Golabchi et al., 2015; Han et al., 2014; Liu et al., 2016). Through machine learning methods, human body joints can be automatically identified from the videos or images. Taking accuracy, efficiency and intrusiveness into account, computer vision-based method is a more suitable method to measure external causes.

External causes can explain the reasons for construction workers’ health and mental problems to some extent, but as external causes take effects through influencing inner causes, inner causes are the intrinsic. Relevant research directly measured the physical indicators of human body with physiological devices or wearable sensors. The physical indicators can be divided into cardiovascular indicators and musculoskeletal indicators. Common cardiovascular indicators include heart rate, breathing rate, skin temperatures and whole-body calorimetry (Faber et al., 2010; Hartmann and Fleischer, 2005; Gatti et al., 2011; Garet et al., 2005). Musculoskeletal indicators contain body orientation, accelerations and surface electromyography (sEMG) (Gatti et al., 2011; Umer et al., 2017). All of the above studies provide efficient ways to collect data reflecting inner causes of workers’ healthy and safe problems. However, they are faced with the same challenge that the signals of devices and sensors are erratic due to the clutter of construction sites.

Based on the above analysis, neither external causes-based research nor the internal causes-based research provides an efficient way to study construction workers’ safety and health problem. On one hand, internal causes are considered as the root causes, but existing methods to measure internal causes are all intrusive; on the other hand, the non-intrusive measurement of external causes has been realized with computer vision. As a result, if the connection between external causes and internal causes is built, it will be possible to study the root causes in a non-intrusive and accurate way. So it is indispensable to build the models connecting the external causes with the internal causes for the identification of the safety and health risks in essence.

Biomechanics provides the exact models that explain how the external causes influence and lead to the internal causes according to kinematics and dynamics theories. Such models enable the establishment of the theoretical connections between workload and postures with intramuscular strains and torques in advance, and then apply the connections to inferring internal causes directly from the observations on the external causes in practice. This approach realizes accurate estimation on worker’s physiological conditions without disturbing normal construction activities. In addition, conventional approaches, which are based on static models, overlook the inertia forces caused by acceleration, resulting in non-conservative estimation. Biomechanical approaches solve this problem through dynamic analysis considering continuous actions.

The purpose of this research is to analyze the work postures via biomechanical methods, which will serve as the base for further analysis, such as workload and physiological analysis, and coupling analysis for workers and temporary structures.

3 The anatomic and biomechanical structure of human

The core biomechanical structure of human is skeleton, serving as the supporting system for the other anatomical structures attached to the skeleton. To construct a functional skeleton system, bones are linked by joints/articulations, while ligaments connect bones across joints and confine the relative rotation of joints. Both tissues have the mechanical properties of elasticity and glutinousness. Muscle is bound to bones by tendons, and generates muscular forces that pull on the bones they are attached to so as to create movement and form diverse postures.

The anatomy and biomechanical structure of human is a complex system, because the mechanical properties of human skeleton and tissues are associated with personalities, such as age and gender. What's more, the stress-strain relationships of muscle and joints are influenced by the rate of loading. Therefore, the comprehensive mechanics of human body appears to be nonlinear and incommensurable.

To simplify the analysis, bones are considered as rigid bars, and joints are set as revolute joints or composite revolute joints in mechanics. Notably, the determination of degrees of free (DOF) are various due to the motions and computational demands. For example, the necessity of building the models of hand knuckles is decided by whether the activity includes grasping. In this paper, the effective skeleton model used on construction sites consists of 17 joints, including hips, chest, neck, shoulders, elbows, wrists, knees and ankles (Fig. 1). The hips joint is identified as the root, and the remaining joints are linked to the root joint as a nested structure of parent-joints and child-joints. These individual joints in conjunction with bones are utilized as the systematic presentation for performing the entire skeletal motions, which is a comprehensive integration of 5 kinematic chains—Spine, left-upper, right-upper, left-lower and right-lower limbs. Thus, all of the joints are able to be converted into the global coordination system based on Denavit-Hartenberg (DH) representation.

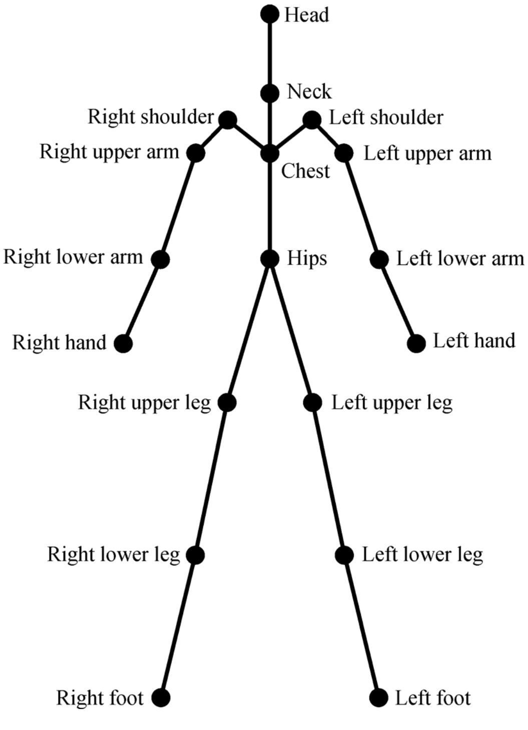

Fig. 1 The biomechanical skeleton model of human body

4 Research method

Figure 2 presents the framework of this research. The aim is to study internal causes from external causes through biomechanics. External causes, in this research, mean postures, and internal causes include joint torque and muscle force. Computer vision is applied to collect posture data. First, videos from common cameras are imported into human body identification software (SkillCapture and Kinovea), and then calibrated manually to automatically and accurately track the body joints parameters (video4-Coach, 2017; Kinovea, 2017). Based on the parameters, the postures can be identified and thus the biomechanical skeleton sequence can be built. Then dynamics analysis is applied to calculate the joint torque and muscle force, which are the internal causes of construction workers' unsafe and unhealthy problems.

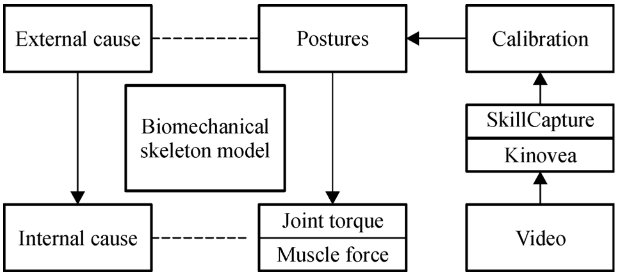

Fig. 2 Research framework

5 Case analysis of typical construction activities

SkillCapture and Kinovea were applied in this research to accurately capture the motion data. Plastering and carrying were selected as the target motions in case study, because (1) they are very common on construction sites, and (2) both of the motions are two-dimensional, and can be presented with 2D models. Experiment subject's clothes were attached with green tags at key joints, such as hands, shoulders, knees and ankles, to facilitate the automatic tracking of these joints from videos. For better accuracy, manual calibration was conducted to verify the error-prone data of postures.

5.1 Case 1—Plastering

Plastering is a common activity on fields, especially in wall and floor construction. The typical postures of plastering are shown in Fig. 3, where the worker was rising and swinging his upper limb by shoulder joint to distribute and smooth the plaster to the wall or floor surface.

Assuming the worker conducted the plastering task slowly and deliberately, the simplified skeleton model is plotted in Fig. 4. The balance equations of force and moment are then listed as follows.

$$F_y - m_{\mathrm{load}}g + m_{\mathrm{arm}}g = 0,$$

$$T_{\mathrm{shoulder}} - m_{\mathrm{load}}gl_{\mathrm{arm}}\cos\theta - m_{\mathrm{arm}}gl_{\mathrm{c}}\cos\theta = 0,$$

where T_{shoulder} and F_y represent the muscular torque and force of right shoulder joint, m_{load} and m_{arm} represent the masses of load and arm, while l_{c} is the distance between right shoulder joint and the centroid of right arm and θ denotes the rotation angle.

Assuming the worker conducted the plastering task with an acceleration of $\ddot{\theta}$, the additional moment of shoulder was required to keep the control of the arm to fulfill the task (Fig. 5). The balance equations of shoulder are transformed as follows.

$$F_y - m_{\mathrm{load}}g - m_{\mathrm{arm}}g - m_{\mathrm{load}}\ddot{\theta}l\cos\theta - m_{\mathrm{arm}}\ddot{\theta}l_{\mathrm{c}}\cos\theta = 0,$$

$$F_x - m_{\mathrm{load}}\ddot{\theta}l\sin\theta - m_{\mathrm{arm}}\ddot{\theta}l_{\mathrm{c}}\sin\theta = 0,$$

$$\begin{aligned} &T_{\mathrm{shoulder}} - m_{\mathrm{load}}gl_{\mathrm{arm}}\cos\theta - m_{\mathrm{arm}}gl_{\mathrm{c}}\cos\theta \\ &-(I_{\mathrm{load}} + m_{\mathrm{load}}l_{\mathrm{arm}}{}^2)\ddot{\theta} - (I_{\mathrm{arm}} + m_{\mathrm{arm}}l_{\mathrm{c}}{}^2)\ddot{\theta} = 0, \end{aligned}$$

where $\ddot{\theta}$ represents the angular acceleration of right shoulder joint and represents the corresponding rotational inertia.

Given the workload and the anthropometry of the worker, the muscular torque is able to be estimated by solving the balance equations rapidly. Dividing the torque by the arm of moment generates the muscular force concurrently. Such solution provides an effective method to assess the internal causes of safety and health issues with sufficient accuracy.

5.2 Case 2—Carrying

The posture of carrying exists widespread on construction sites due to the complex venues conditions. Human body will fail to keep balance when the combined barycenter of the worker and objects is beyond the support of feet foundation, i.e., the horizontal distance between the combined barycenter and the ankle joints is greater than a certain threshold.

The preliminary model divides the whole body into upper part and lower part as illustrated in Fig. 6. The horizontal distances between the human body's centers of mass and the ankle joints are e_u and e_l respectively, while the distance for demarcation point and object is e and d. The horizontal distance l between the combined barycenter and ankle joint satisfies the following equations when the body is in balance.

$$m_u g e_u + m_{\mathrm{load}}gd - m_l g e_l = m_{\mathrm{c}}gl.$$

Once the l increases to levels over the threshold of the feet foundation, the worker will fall down. Apart from balance, the band moment on waist joint is also required to be less than the maximum waist torque that human can bear.

$$T_{\mathrm{waist}} = m_u g(e_u + e) + m_{\mathrm{load}}g(d + e).$$

Assume the rate of carrying tasks is extremely slow and the individual barycenter of each part of human body is located at the middle of bones, the preliminary model is refined as Fig. 7. Thus, the balance equations of carrying are reconstructed herein.

$$\begin{aligned} &-e_l(m_1 + m_2 + m_3) \\ &= \frac{1}{2}m_1 l_1\cos\theta_1 + m_2\left[l_1\cos\theta_1 - \frac{1}{2}l_2\cos(\theta_2 - \theta_1)\right] \\ &\quad + m_3\left[l_1\cos\theta_1 - l_2\cos(\theta_2 - \theta_1) + \frac{1}{2}l_3\cos(\theta_3 - \theta_2 + \theta_1)\right], \end{aligned}$$

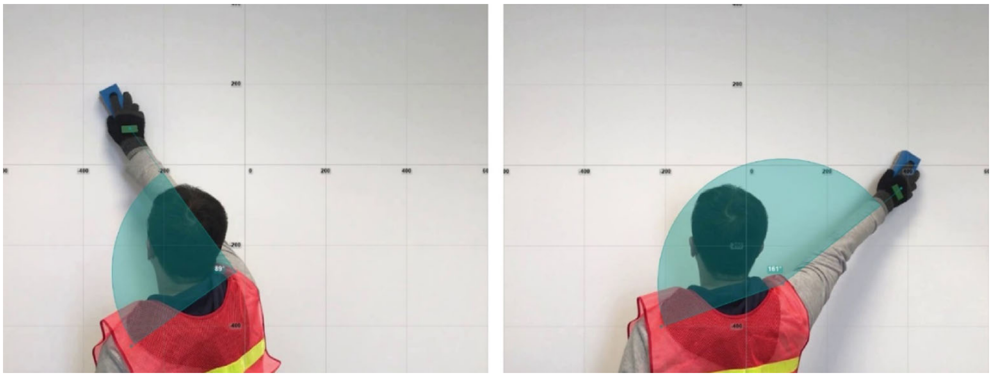

Fig. 3 The typical postures of plastering

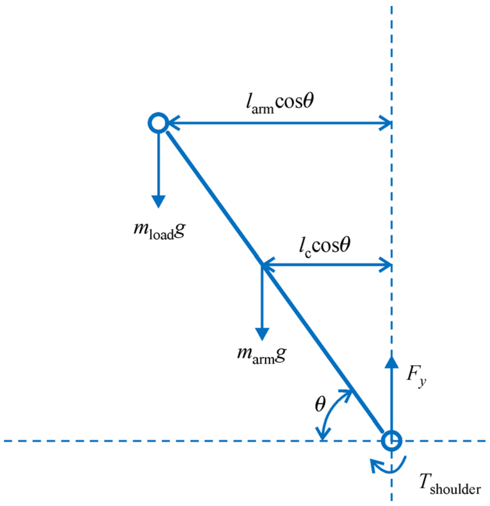

Fig. 4 The static mechanical model of plastering

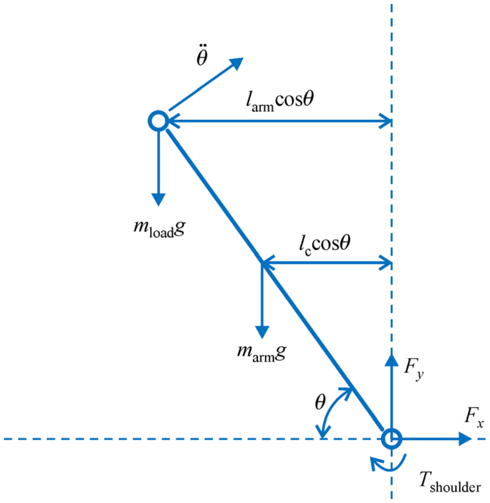

Fig. 5 The dynamic mechanical model of plastering

$$(e_u+e)(m_4+m_5+m_6+m_7+m_8)$$
$$=\frac{1}{2}m_4l_4\cos\theta+m_5[l_4\cos\theta+l_5\cos\theta(\theta+\theta_5+\theta_6-\pi)]$$
$$+m\left[l_4\cos\theta+\frac{1}{2}l_6\cos(\pi-\theta-\theta_5)\right]$$
$$+m\left[l_4\cos\theta+l_6\cos(\pi-\theta-\theta_5)+\frac{1}{2}l_7\cos(\theta_7-\theta-\theta_5)\right]$$
$$+m[l_4\cos\theta+l_6\cos(\pi-\theta-\theta_5)+l_7\cos(\theta_7-\theta-\theta_5)],$$

$$d=l_4\cos\theta+l_6\cos(\pi-\theta-\theta_5)+l_7\cos(\theta_7-\theta-\theta_5),$$

$$-e=l_1\cos\theta_1-l_2\cos(\theta_2-\theta_1)+l_3\cos(\theta_3-\theta_2+\theta_1),$$

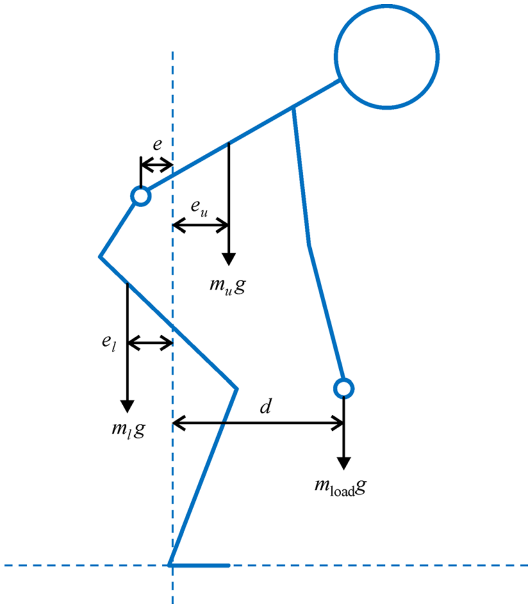

Fig. 6 The preliminary mechanical model of carrying

$$\theta=\theta_4-\pi+\theta_3-\theta_2+\theta_1.$$

Although the physical and mechanical properties of human body parts are associated with personalities, the proportions of lengths and weights of body segment to height and weight of the whole body are almost fixed. According to Tables 1 and 2 (Plagenhoef et al., 1983), the accurate internal muscular torque is recomputed.

$$e_l=[-0.2204\cos\theta_1+0.1269\cos(\theta_2-\theta_1)$$
$$-0.0144\cos\pi(\theta_3-\theta_2+\theta_1)]h,$$

$$e_u=[-0.2470\cos\theta_1-0.2320\cos(\theta_2-\theta_1)$$
$$+0.0930\cos(\theta_3-\theta_2+\theta_1)$$
$$-0.1429\cos(\theta_4+\theta_3-\theta_2+\theta_1)$$
$$+0.0269\cos(\theta_5+\theta_4+\theta_3-\theta_2+\theta_1)$$
$$+0.0168\cos(\theta_6+\theta_5+\theta_4+\theta_3-\theta_2+\theta_1)$$
$$-0.0094\cos(\theta_7-\theta_5-\theta_4-\theta_3+\theta_2+\theta_1)]h,$$

$$d=[-0.2080\cos(\theta_4+\theta_3-\theta_2+\theta_1)$$
$$+0.1720\cos(\theta_5+\theta_4+\theta_3-\theta_2+\theta_1)$$
$$-0.1570\cos(\theta_7-\theta_5-\theta_4-\theta_3+\theta_2-\theta_1)]h.$$

The horizontal distance between the barycenter and ankle joint is

$$l=\frac{0.5296me_u+m_{\mathrm{load}}d-0.4416me_l}{0.9712m+m_{\mathrm{load}}}<l_{\max}=0.0143h.$$

The maximum load to stay balance is

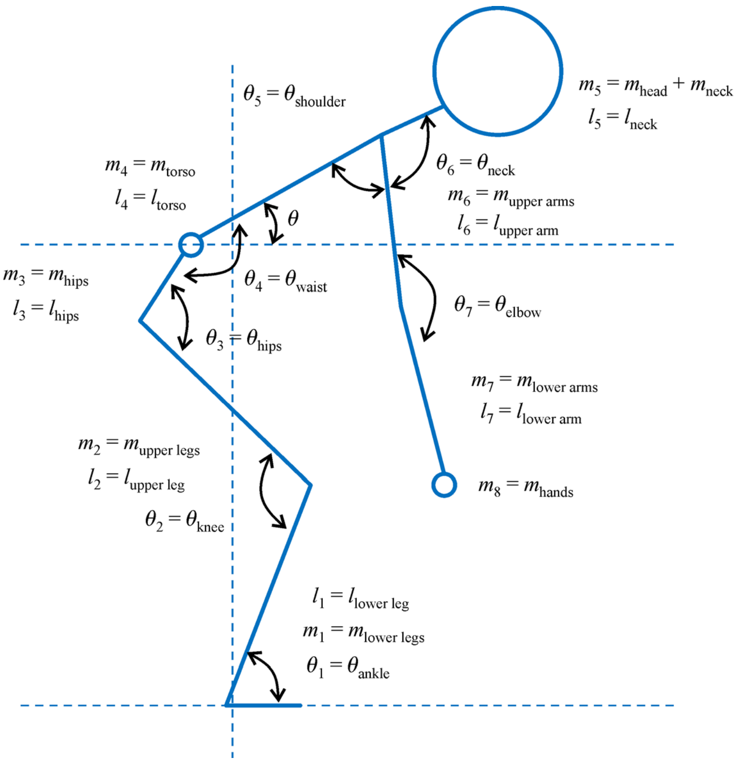

Fig. 7 The detailed mechanical model of carrying

Table 1 Percentages of total body weight

Gender	Lower leg/%	Upper leg/%	Hips/%	Torso/%	Head & neck/%	Upper arm/%	Lower arm/%	Hand/%	Foot/%
Male	4.75×2	10.50×2	13.66	33.16	8.26	3.25×2	1.87×2	0.65×2	1.43×2
Female	5.35×2	11.75×2	15.96	29.26	8.20	2.90×2	1.57×2	0.50×2	1.33×2

Table 2 Percentages of total body height

Gender	Lower leg/%	Upper leg/%	Hips/%	Torso/%	Head & neck/%	Upper arm/%	Lower arm/%	Hand/%	Foot/%
Male	24.7	23.2	9.3	20.8	10.75	17.2	15.7	5.75	24.7
Female	25.7	24.9	9.3	20.8	10.75	17.3	16.0	5.75	25.7

$$m_{\text{load}} < \frac{0.9712 l_{\max} - 0.5296 e_u + 0.4416 m e_l}{d - l_{\max}} m.$$

The corresponding bending moment of waist is updated as

$$T_{\text{waist}} = 0.529 mg(e_u + e) + m_{\text{load}} g(d + e).$$

6 Results and discussion

Through the marked videos with the rotate angles of joints from the right side of the worker (Fig. 8), the carrying process was quantified and tracked objectively as shown in Fig. 9. The author first marked and calibrated the key joints in the first frame of the video, and then the software would track the change of these joint angles automatically.

To compare the effect on the muscular torques of waist, workloads from 0 to $2mg$ were calculated. The changing curve representing the ratio of waist torques over mgh during the carrying process is plotted in Fig. 9. It can be found that during the process of lifting, the rotation angles of wrist and shoulder changed most sharply. Other joints changed in a fairly small range, including ankle, knee, hips, neck and elbow. The result is consistent with the common sense of lifting motion, demonstrating the reliability of the motion capture method.

As one of the most vulnerable joints of construction workers, waist joint was selected as the sample of further analysis. By comparing Figs. 9 and 10, it can be found that

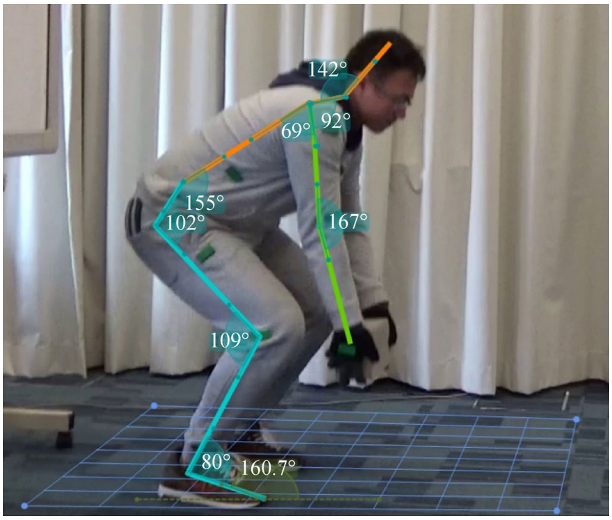

Fig. 8 The marked skeleton from videos

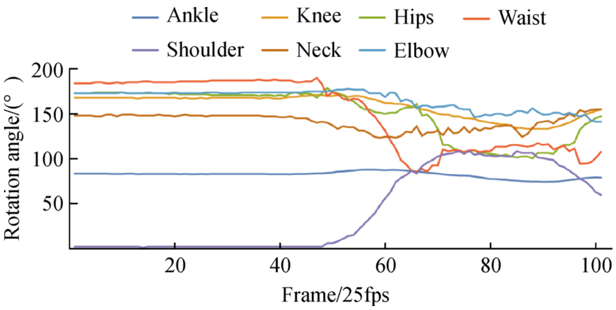

Fig. 9 The rotate angles of joints of carrying postures

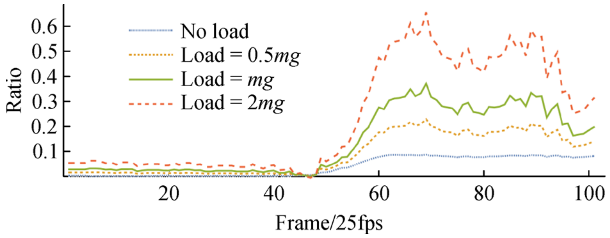

Fig. 10 The waist torques during carrying process

the waist torque changed along with the waist rotation angle. At the beginning of lifting, the waist moment was relatively small, and then increased dramatically until reaching the steady state. At the same time, the rotate angle of waist joint also deceased sharply. It is worth mentioning that the peak value occurred at around the 70th frame and the 90th frame, which is just the beginning and the end of the flat period of waist rotation angle. Thus, more attention should be paid to the two moments during the process of lifting. Besides, with the increase of load, the waist torques also increased with it. Since the arm of waist moment was relatively long, a tiny increase of the carrying workload had a significant impact on waist moment. By comparing the internal causes and external causes, the plot revealed that the maximum waist torques and maximum waist angles appeared at almost the same time, in terms that the low back pain of construction workers was strongly attributed to the bending postures. Thus, the waist WMSDs of construction workers can be alleviated or prevented through adjusting the working process to contain few postures with large waist angles.

7 Conclusions and future research

This research quantified the construction motions by tracking and recording the key joints from videos, established the skeleton model based on anthropometry and physiology of human body, and then analyzed the influences of external causes on internal causes from the perspective of biomechanics. The two case studies examined and validated the approach of using biomechanics to realize the rapid and accurate assessment of balance, joints force and torques, and maximum workload from postures. The models and approaches can be widely implemented to various postures on construction sites, and the results enable superintendents to assess the safety and health risks of labor crew objectively.

Although the proposed approach is objective and rapid, the assumptions limit the implementation in practice because the construction activities on fields are too complex to be simplified and computed. Moreover, the tracked posture from a single video camera is 2D, which is insufficient to provide the realistic rotate angles of joints in 3D. Thus, the future research will focus on the motion captures in 3D and the analysis of complex motions.

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