Digital Human Modeling for Physiological Factors Evaluation in Work System Design

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Abstract. This paper aims to develop a theoretical framework for physiological factors evaluation in work system design, and the goal has been achieved by combining principles and techniques derived from Digital Human Modeling (DHM). In more specific terms, geometrical, biomechanical, and graphical models are constructed to realize the simulation of worker's physical status in the virtual working environment, then to detect and evaluate work-related musculoskeletal disorders (WMSDs) which have a great potential of causing occupational impairment and disability. Furthermore, the ultimate object of this proposed framework is to fit the work system to the worker, and prevent the WMSDs from the original design phase.

Keywords: Work-related Musculoskeletal Disorders, Digital Human Modeling, Work System Design.

1 Introduction

Despite the fact that automatic operation plays a predominant role in industrial production, manual operation still accounts for a large proportion in virtue of the agility, flexibility and dexterity of human being. However, manual workers are easily exposed to a variety of hazardous work environment factors which have been the causes of negative effects upon the workers' physical health status and the work system performance from time to time.

WMSDs are heterogeneous group of chronic injuries or disorders of the body parts and tissues like muscles, nerves, tendons, ligaments, joints, or bones which develop over time due to work-related awkward and static postures, frequent and highly repetitive activities, forceful exertion, long duration as well as short cycle operations, they are serious occupational safety and health problems that closely related to a broad range of manual workers' physiological discomfort, fatigue, pain, injury and disability during work or at rest. Normally, there is no doubt that these common health risks can adversely affect a significant scale of workers' performance either through increasing the error rates or decreasing the workload which has been recognized as the reason of compromising the value of work system output and even the profits of company.

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The structure of this paper is illustrated as follows: firstly, an overview of WMSDs and DHM is given to make the background clear and transparent; secondly, geometrical model, biomechanical model, and graphical model are introduced to represent the DHM tool; thirdly, a theoretical framework is developed to lay out the strategy of using DHM to demonstrate the work functions and evaluate the physiological factors, and this simulation method is performed to assess work postures and motions, then prevent the occupational hazards; finally, effects of the proposed framework, either positive or negative, are discussed in the context of a systemic analysis, and the feasible future work is presented for research continuity.

2 Background

2.1 Work-Related Musculoskeletal Disorders

The musculoskeletal system which is made up of bones, muscles, joints, tendons, ligaments, and other connective tissues consists of two interrelated systems, one is the skeletal system that provides a structure for physical support of the body, gives protection for the internal organs and fragile body tissues, realizes principal function of body movement, stores minerals, produces blood cells, and regulates incretion, the other is the muscular system that maintains posture, causes motion, stabilizes joints, circulates blood, and generates heat.

WMSDs describe disorders and diseases of this musculoskeletal system which are suspected to have been caused and exacerbated by a wide extent of work-related risk factors such as abominable work conditions, disorganized working process, shift work and long work hours, excessive force and sustained postures, etc. These disorders include degenerative and inflammatory syndromes of the muscles, skeleton and related tissues like tendons, joints, ligaments, bursae, cartilages, blood vessels, and peripheral nerves, for instance, myalgia, arthritis, osteoarthrosis, tenosynovitis, sciatica, bursitis, and so forth [1].

Disorders of the skeletal system contain sprain, luxation, and fracture. A sprain is an injury to the ligament or tissues around a joint that caused by a sudden fall or twist. A luxation is a joint dislocation occurs when bones are forced out of the right position in a joint. A traumatic bone fracture means the bone is completely or partially broken or cracked while an intense physical force is being exerted to it accidentally, and a pathological bone fracture is a bone lesion that arises from some underlying diseases.

Common muscular system injuries include strain, contusion, and cramp. A strain occurs when the muscle and adjacent tissues are extremely stretched or possibly ripped by a severe tension force. A contusion is a relatively minor hematoma of skin, subcutaneous tissue, and muscle that caused by a strong compression force. A cramp is a painful, sustained, and involuntary contraction of the skeletal muscle due to muscle fatigue and rigidity.

2.2 Digital Human Modeling

DHM is a simulation tool that provides a virtual representation of human beings in the simulated working environment for assessing the biomechanical attributes of human bodies with rapid computational efficiency, the skeleton structure and graphical appearance of virtual human are set up to realize the dimensional and physical properties from the interior to the exterior, thus to predict potential occupational fatigue and disorder risk. In general, the core of DHM is that it investigates multiple aspects of human postures and calculates the anthropometric elements quickly and objectively by replicating the on-going operation of complex work systems based on the database of recorded real human postures and motions.

The specific DHM tools like Ramsis, Siemens NX Human Modeling, Ergoman, Santos, CATIA, and DELMIA have been extensively utilized as proactive and available approaches to visualize and evaluate the interaction of workers and work systems from ergonomic aspects like visibility, functionality, scalability, and comfort in the fields of manufacturing, automobile, aerospace, military, healthcare, etc [2]. Hu et al. used five indices to assess the impact of ergonomic measurements feedback via a simulated drilling task operated by male manufacturing workers in the virtual environment [3]. Chang and Wang applied a visual workplace evaluation method to assess automobile assembly tasks by integrating dynamic digital environment simulation and biomechanical posture analysis [4]. Tian and Duffy implemented a DHM based Job Risk Classification Model to dynamically evaluate the corresponding task risk via calculating velocity and angular velocity of specified body segments/joints, in addition, they also analyzed potential errors to test the validity and reliability of this upgraded model [5]. Jung et al. combined the DHM with a commercial CAD system to implement the knowledge-based parametric modeling function of vehicles, and this integrated framework was carried out to gain optimized interior design parameters for ergonomic evaluations of various human-vehicle interactions [6]. Hanson et al. modified a DHM tool and utilized it to illustrate the cost efficiency and user-centered design processes of a health care bathing product. In this DHM working process scenario, joint range of motion and preferred bathing postures were defined, then description and appearance of the manikin was customized to fit the requirements [7].

2.3 Objective

The general objective of this research is to propose a theoretical framework associated with the digital human tool under which different aspects of human elements and data can be simultaneously integrated and simulated to realistically visualize the complex task oriented motion and interaction of real worker and workstation for multivariate assessment of physiological factors at the early stage of work system design, in order to concurrently evaluate biomechanical discomfort and analyze potential WMSDs exposures for identifying workplace and work task problems, then establish the adjustment of work environment to accommodate the workers for preventing them rapidly and economically.

3 Methodology

3.1 Geometrical Human Modeling

Geometrical human modeling is a modeling tool and technology of generating data structures and defined functions for presenting the finite dimensions, angles, and such characteristics of a desired human body shape as realistically as possible, and it focuses on the adequate numerical acquisition, simulation, and representation of the anthropometric features in order to quantize the numeric values of physiological factors in detail. Moreover, it provides fast visualization and parameterization of the body as well as defines these two or three-dimensional (3D) shapes efficiently by estimating the geometrical constraints of body joints and performing the mathematical calculations of human actions.

This geometrical approach is widely used in various computer-based application fields such as product design, mechanical engineering, animation design, medical image, etc. Wang proposed a feature based parameterization algorithm for parametric mannequin design according to the semantic feature extraction technique and symmetric detail mesh surface of the human body in fashion industry [8]. Wang et al. gave a detailed survey on existing parameterized 3D human body modeling and skin deformations methods which are primitive construction methods named rod-like model, surface model, volume model, and composite multi-layer model, model reconstruction methods based on 3D body scanning, contour data, and image, as well as sample interpolation synthesis methods [9]. Volkau et al. formulated a suitable 3D geometric venous segmentation algorithm of the human intracranial vasculature system for education and clinical applications by proposing three geometrical models based on circular, elliptic, and free-shape cross sections [10].

3.2 Biomechanical Human Modeling

Biomechanical human modeling studies the properties of the muscle, skeleton, and soft tissue when human performs physical activities like static postures or dynamic motions from the perspective of physiological kinematics that muscles generate tension through connective soft tissues which transfer it to move bones around joints. It is a valuable tool for ergonomic evaluations not only because of understanding musculoskeletal system capabilities, but also due to providing testable hypotheses of mechanical behavior variation and predicting the posture and trajectory of human body.

The muscle model is used to simulate the actual molecular structure and internal functioning of a muscle which represents the mechanical response of muscle contraction by emulating three primary relationships named force-length, force-velocity, and stimulus-tension curves when muscle fibers generate tension. The skeleton model is formulated in terms of an articulated multi-body dynamic system which takes into account the parameters of joint moment strengths, joint torques, and joint movement ranges, it aims at contributing to describing the posture, velocity, and acceleration of human motions by a set of dynamic equations. The soft tissue model represents the physically-based deformations of soft tissues via proposing the exponential strain energy functions for real-time computation of deformability which exhibits mechanical characteristics like nonlinear stress-strain behavior, anisotropy, and linear viscoelasticity.

3.3 Graphical Human Modeling

Graphical human modeling is central to the visual representation of biomechanical human body structure, and it typically consists of two basic components: realistic modeling of articulated skeleton structure and graphical appearance of virtual body. The skeletal model is composed of a suitable kinematic tree based revolute joints with various degree of freedom, and along with bones as rigid links at the articulation sites, this linear and angular displacements of the whole body is divided into 12 joints named neck, shoulder, elbow, wrist, hip, knee, and ankle, as well as 14 segments named head, body, upper arm, forearm, hand, thigh, shank, and foot. The visual model provides the visual feedback component which includes multi-planar interactive image display of human body to get approximate shape, size and relative proportions of real human.

The graphical human model encompasses the kinematic properties and visual features of human behavior as the foundation for shape initialization, pose estimation and motion detection, this vision-based interpretation is performed consistent with human factors principles and practices. Shape initialization is obtained by utilizing a scatter data interpolation model to deform the average shape, pose estimation is a process of pose configuration evaluation from single monocular images, in addition, motion detection refers to monitoring the change in position of an object with respect to its surroundings.

4 Framework

A DHM based theoretical model is formulated to simulate the biomechanical attributes of manual handling operators and investigate working postures and activities while the workers performing the tasks in order to predict potential WMSDs and adjust the workplace and work practices. The center of this Physiological Evaluation Framework is a simulation structure along with the computational estimation, as shown in Figure 1.

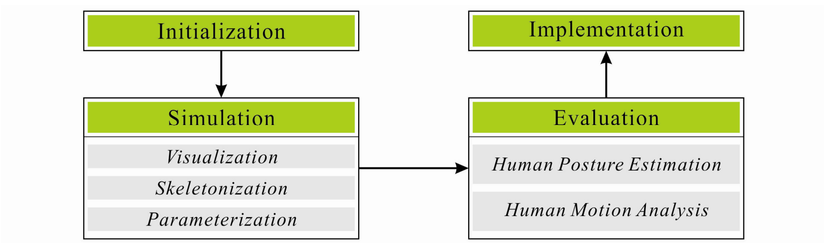

Fig. 1. Physiological Evaluation Framework

4.1 Initialization

The initialization step presented in this paper can be formulated as the process of providing a conventional model approximating the size, shape, appearance, kinematic structure to obtain an initial hypothesis about the pose and position of the worker, and to define the boundary conditions under which the proactive gestures and motions can take place for interpreting and tracking body behavior. This initial hypothesis deals with a better extraction and representation of body motion by initializing various values of the geometric and dynamic properties, as well as biologic characteristics which will be synthesized in an effort to anticipate and evaluate physical body intentions before they occur. It is a fundamental and key channel to bring in prior knowledge and data source about familiar body configuration and reconstruction which can help to constrain and prevent the production of unrealistic body acquisition and pose estimation due to the high dimensional pose state space.

4.2 Simulation

The simulation step enables a rapid and virtual representation of human bodies to facilitate assessing multiple aspects of physical work-related features which are commonly cited as risk factors for WMSDs. It includes three essential phases named visualization, skeletonization, and parameterization, as depicted in Figure 2.

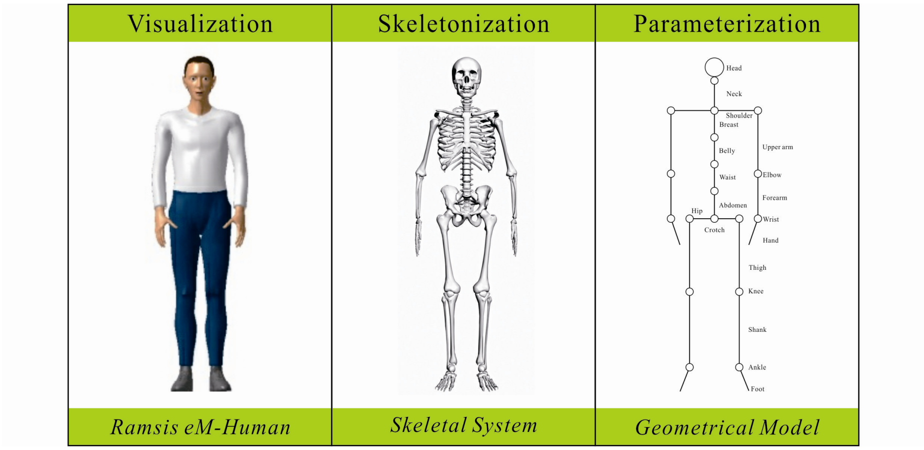

Fig. 2. Simulated Human Model

Visualization. Human body visualization implies the immersive image acquisition progress through computer graphics and image processing to achieve digitally constructed transformation, selection, and representation of a real object. It focuses on converting nonobjective human data into concrete imagery, so as to present visual information, communicate graphical messages, and explore the implicit or explicit understanding of these data. In particular, the realistic visualization of human body can be broken down into two successive procedures, the first one disposes rigid skeleton structure of the body, and the second one deals with rendering of muscles, skin, and such non-rigid tissue system. Generally, the visualization phase aims at recognition and tracking of human gestures and actions in a suite of image sequences.

Skeletonization. Human body skeletonization is a common preprocessing operation in pattern to vector conversion, and it is aimed to extract the central path based shape features which give an illustrative definition of the skeleton, and represent the general form of a body with all soft tissue eliminated. The skeleton extraction provides a simple and real-time way of implementing layer by layer erosion and distance transformation for the purposes of detecting boundaries extracted as the representative descriptor of human posture and creating an accurate description of bodily motion. It is articulated in three stages named silhouette detection, mass center to extremities calculation, and structural pattern recognition for the full body skeleton articulation and trajectory measurement in relation to their original properties of the shape such as length, width, position, orientation, etc.

Parameterization. Human body parameterization represents the numerical implementation of biomechanical human posture features creation and modeling, it comprises geometric information extraction together with topological motion translation for parameterized transformation of the static and dynamic body system. In other words, mathematically articulated interacting models are proposed to formulate and characterize both the geometrical structures and approximated motion movements of a real human body from the kinematics and dynamics point of view. The exploration of kinematic model begins with concise description of links parameters as well as joints constraints, and it is complemented by means of concatenating state vectors in a general mathematical formulation of static states. It is emphasized that the dynamic model describes linear position and angular velocities evolution of the motion vector system over time.

4.3 Evaluation

The evaluation step consists of two relatively independent but mutually complementary phases, namely human posture estimation and human motion analysis that have been developed to objectively assess physiological factors associated with WMSDs.

Human Posture Estimation. Human posture estimation intends to provide a representative method for assessing the degree of suitability between the work environment parameters and the anthropometric dimensions of the worker, as well as evaluating postural load which depends on the specific operational context during working time, in order to prevent discomfort, fatigue, and injury caused by awkward working postures of trunk, arms, and legs which place their joints away from the natural position for a long time. The Ovako Working Posture Analysis System (OWAS) is an analytical and quantitative method which enables calculating worker's posture load and time expenditure for each activity at workstation by means of analyzing the postural data, and it is heuristically implemented to obtain the improvement of problematic working postures negative for workers. Additionally, OWAS categorizes the whole body posture into four major body segments named trunk, arms, legs, and head/neck based on a systematic classification combined with observations of work tasks, it is described and measured by a four classes posture ranking system in which normal posture means no intervention required, slightly harmful posture should be corrected in near future, distinctly harmful posture needs corrective action as soon as possible, and extremely harmful posture must be improved immediately.

Human Motion Analysis. Human motion states the continuous movement or change in body position with respect to time, motion analysis is critical in the field of WMSDs prevention, and it is divided into three processes: motion recognition, motion segmentation, and motion evaluation. Human motion recognition describes the basic elements of human activities in terms of position, direction, angle, trajectory, velocity, acceleration, time, duration, and so forth. Human motion segmentation decomposes human activities into a sequence of actions, and it is a preprocessing stage for capturing the univariate or multivariate motion data before and after an operation, then analyzing the computational human motion model with high spatial and temporal accuracy. Human motion evaluation presents the detailed foundation, principle, and procedure for coherent clusters of working actions assessments. Specifically, it acquires motion captured parameters as indices to indicate the worker's physiological capacity level, then elucidates the desirable motion features and estimates these parameters in a hierarchical order based on experimental investigations, the difficulty of this process derives directly from complexity of and diversity of human movement.

4.4 Implementation

The implementation step provides guidance regarding how to realize all the modification requirements obtained during the previous steps, and execute specific improvement progresses based on essential features of operational work system. It is viewed as a vital system development process that continually seeks to make adjustments to workplaces, embed better workflows, as well as monitor achievements against objectives, for the purpose of creating smarter work system to accommodate worker's needs. The key focus is to properly carry out the modification and execution stages, systematic modification stage analyzes and determines if the proposed adjustments are appropriate for reducing the level of WMSDs risk, deliberate execution stage is performed to meet work system design demands until the result is acceptable. This dynamically optimized step is required to be used as a fundamental element in turning work system mission, vision, and values into reality.

5 Conclusion

In conclusion, this paper introduces a theoretical approach to illustrate how a modified DHM tool is utilized to assess worker's physiological factors within the context of interactive visualization environments. Graphical, biomechanical, and geometrical models are used in the simulation of work postures and activities, thus to furnish a basis for evaluating the WMSDs which have negative consequences both for the worker and work system performance, and then adjust the relevant work system elements to prevent risks. Future research will concentrate on providing experimental intervention and mathematical evaluation for multifactorial muscular system and skeletal system disorders measurement of human postures and motions, for the sake of confirming the feasibility of this theoretical framework as integrating DHM into physiological factors evaluation in work system design. In addition, the disparity between simulation results and real practice performances will be demonstrated to represent the reliability and accuracy of simulated human model.

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