Evaluation of human joint angles in industrial tasks using OpenSim

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***Abstract*—The musculoskeletal disorders represent one of the most common problems in industrial environment; they impact the health of workers and employees. In this work we present a preliminary study towards the use of biomechanical models for improving classic methods for ergonomic assessment in industry. To this end, we use OpenSim, a software for biomechanical simulation and analysis. With OpenSim, we reconstruct the human motion corresponding to the execution of industrial tasks, performed in laboratory settings. In particular, we compute the evolution over time of the joint angles that, according to a classic observation method for ergonomic assessment, are needed to evaluate the risks associated to the musculoskeletal disorders for the upper limb.**

***Index Terms*—industry, ergonomics, digital human model, biomechanics.**

I. INTRODUCTION

The recently growing interest in *health at work* aims at prolonging employees' working lives, by reducing the risks associated to musculoskeletal disorders (MSD). As a matter of fact, in Europe, the registered occupational diseases affect almost 50% of industrial workers (70–80 million) [1]. The 45% of the MSD cases afflict the upper limbs, the 38% afflict the back, and 17% afflict lower limbs. In the USA, the U.S. Bureau of Labor Statistics [1] reports around 650,000 work–related MSD, resulting in costs to employers of over 20 billion dollars (including worker compensation and medical expenses).

Frequent repetition of the same task, excessive forces induced on the joints, and awkward postures are cited as the most important ergonomic risk factors; indeed, they are listed as a major causes of MSD in industrial workplace [2]. Several MSD can be caused by common industrial task (lifting and carrying, pushing and pulling, handling of low loads at high frequency), behavioral errors, by personal predispositions. The latter are influenced by many individual features such as: gender, age [3] and anthropometric parameters [4], previous or ongoing pathologies, paraphysiological states, lumbar motility, physical training, muscular strength, postural attitude, smoking habits, risk factors related to hobbies and sports [5].

In the context of Industry 4.0, the evaluation and monitoring of the *human ergonomics* during the execution of industrial activities is playing a major role. The human ergonomics basically depends on following factors: (i) working posture; (ii) load; (iii) frequency of the task repetitions. For the evaluation of these factors, the evaluation of joint angles and joint torques over time is required. Obtaining these information without auxiliary technologies is difficult. So, technologies and methods able to track and reconstruct with accuracy the human movements are necessary.

In this context, this work presents the joint motion reconstruction and analysis of a subject during the execution of selected industrial tasks. For this aim we use: (i) an optical–based system for tracking of human motion; (ii) a software for biomechanical simulation and analysis (OpenSim [6]). For measurement purposes, we choose an optical–based system, as this technology is the most accurate for tracking of human motion. We conducted the experiments at ERGOS Lab, the Laboratory of Advanced Measures on Ergonomics and Shapes at CeSMA, University of Naples Federico II. Ideed, the choice of OpenSim allows: (i) to scale the digital human model (DHM) based on anthropometric characteristics; (ii) to generate a muscle–driven simulation of a movement; (iii) to compute the DHM joint angles and torque; (iv) to find the set of activated muscles during the movement. Simulations are generally evaluated by experimentally measured kinematics, kinetics, and electromyography (EMG) patterns. This is a preliminary work towards the development of biomechanical–based methods for ergonomic assessment of industrial workplaces. Indeed, they have recently shown interesting capabilities as advanced approaches for risk–assessment of work–related MSD [7], [8].

The paper is organized as follows. Section II contains a brief review of the methods using for evaluating muscoloskeletal disorders. Section III describes the framework and Sec. IV the experiments and results. Finally, Sec. V reports the conclusions of this preliminary work and the future potential applications.

II. STATE OF THE ART

This section reports: (1) rules for risk assessment of work–related MSD; (2) overview of the current empirical methods to assess MSD; (3) overview of the digital human models (DHM) used to evaluate the human posture.

1) Rules for risk–assessment of work–related MSD: The rules for evaluating the risks associated to MSD come back to 2003. They are: UNI-EN 1005-2 (European one) and ISO

[1] `https://www.bls.gov/`

11228-1 [2] (International one). Then, in 2007, the ISO 11228 standard was divided in three main parts:

Part 1 (lifting and carrying): the standard suggests the application of the method illustrated by National Institute of Occupational Safety and Health (NIOSH [9]).

Part 2 (pushing and pulling): the standard suggests the application of "Psychophysical Tables" introduced by Snook and Ciriello [10].

Part 3 (handling of low loads at high frequency): the standard suggests the application of the OCRA method [11].

2) Empirical methods for risk–assessment of work–related MSD: The most adopted approaches in the literature are: Ovako Working Posture Analysing System (OWAS) [12], Rapid Upper Limb Assessment (RULA) [13] and Rapid Entire Body Assessment (REBA) [14]. These methods have been accredited and validated with respect to the previously defined rules [15] [16]. OWAS and REBA consider the whole body and they can be applied to non-sedentary jobs; instead, RULA considers only the upper limb and it examines the sedentary jobs. Since we are interested in general industrial tasks that only concern the upper limb, we rely on the RULA method to define the joint angles to be tracked (neck,shoulders and arms).

3) Digital human models: Digital human models are used to replicate the human activity in a virtual environment [17]. DHM softwares are divided in two main groups: (i) Classic DHM softwares (as Siemens Tecnomatix Jack [3]); (ii) Biomechanical–based DHM softwares which implement biomechanical models of the human body with an accurate dynamic simulation engine (as OpenSim [4]). In the first case, the DHM software can provide only joint angles and torques [18]. In the second case, in addition, the DHM software can provide also muscle activation. An exhaustive list of the digital human models is reported in [19].

III. OVERVIEW OF THE METHODOLOGY

The methodology used in this work for biomechanical–based joint motion reconstruction in overhead tasks briefly summarizes in the following steps:

1) Selection of industrial tasks of interest.
2) Selection of joint angles of interest for ergonomic assessment in overhead tasks.
3) Optical–based system for tracking of overhead tasks.
4) Biomechanical–based reconstruction of the joint angles of interest.

For the first point, we select overhead tasks. Indeed, we are interested in ergonomic assessment of workplaces for the automotive industry; in this scenario overhead tasks are the most common industrial tasks [20], [21]. These tasks can be defined as sedentary jobs since the workers carry out the industrial task keeping constant the position of the legs.

[2]https://www.iso.org/standard/26520.html

[3]https://www.plm.automation.siemens.com

[4]https://opensim.stanford.edu

For the second point, we select the joint angles which the RULA method uses for ergonomic assessment [13]. Indeed, this method, even if often based on simple observation, is still one of the most adopted for posture evaluation related to the upper limb. The joint angles required for evaluating the worker's posture according to the RULA, and thus, the angles of interests for this study (more details in Sec. IV), are:

- shoulder flexion–extension, abduction and rotation;
- elbow flexion–extension;
- trunk flexion–extension;
- neck flexion–extension.

For the third point, we select optical–based system as they are the reference for tracking of human movements [22], [23].

For the fourth point, we use OpenSim, as this software is the reference for biomechanical studies and dynamic simulations. In this preliminary study, we are only interested in exploiting the kinematics capability of this software. Indeed, kinematics is the starting point for additional evaluations which are possible with this software, mainly related to inverse dynamic computation and evaluation of muscles activation.

IV. EXPERIMENTS

In this section we present the experimental setup and the results of this preliminary study.

A. Participant and industrial tasks

One volunteer subject (right–handed, male, age: 24 years, mass: 79.3 kg, height: 1.78 m, arm length: 63cm) was involved in the experiments. For the current work, we performed the following overhead tasks:

- Leveraging: the subject was asked to stay with the right hand above the head for about 7 seconds (working posture) and about 4 seconds with the arm below the shoulder (reset position) while having a wrench in the dominant hand. The weight of the wrench is 270 g. Some snapshots of the task execution are shown in Fig. 1.
- Drilling: the posture is similar to previous one; again, the subject was asked to stay about 7 seconds in working posture and about 4 seconds in reset position, while having a drill (turned on) in its dominant hand. The weight of the drill is 1850 g. Some snapshots of the task execution are shown in Fig. 2.

During the task execution, the subject was asked to remain parallel to the working plane defined by a rectangular–shaped working pole (see Fig. 1, 2); from it, he was at a distance of 23 cm (36,50% of the arm length). For each of the two tasks, we performed the trials at two different working heights on the working pole. The height of the first configuration h_1 was set equal to h_1 =1.83 m (102,8% of the subject height); the height of the second configuration h_2 was set equal to h_2 =2.00 m (112,3% of the subject height). For each configuration, three cycles of the tasks were conducted by the subject.

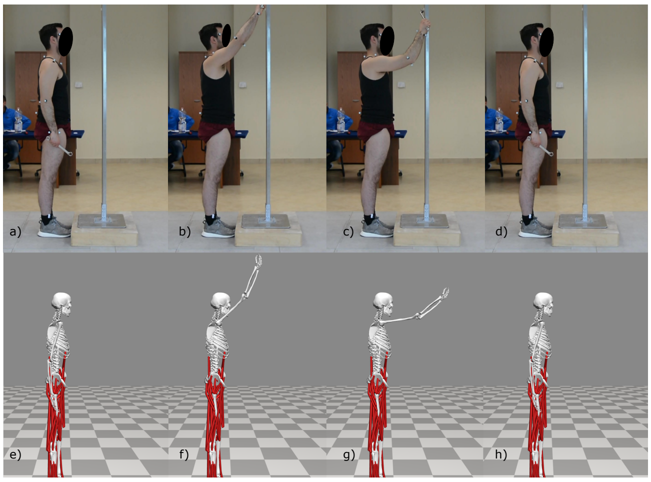

Fig. 1. Leveraging task. The figure shows the main steps in performing the task. (a)–(b): Real pictures; (e)–(h): OpenSim model. (a) and (e), (d) and (h): reset position; (b) and (f), (c) and (g): working posture.

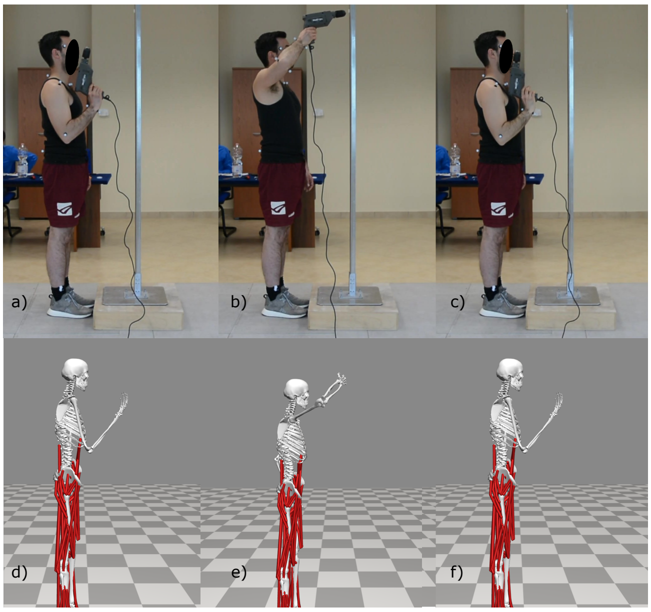

Fig. 2. Drilling task. The figure shows the main steps in performing the task. (a)–(c): Real pictures; (d)–(f): OpenSim model. (a) and (d), (c) and (f): reset position; (b) and (e): working posture.

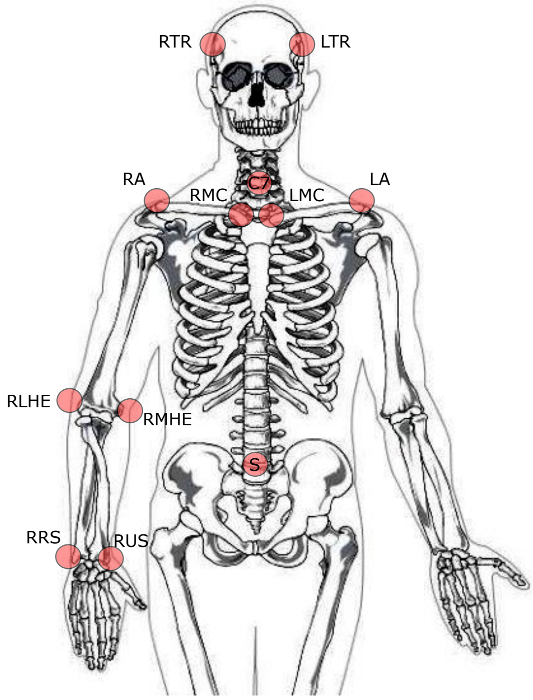

Fig. 3. Market set on the upper body.

B. Experimental equipment and measurement protocol

The tracking system used in the experiments is a motion capture systems composed by ten infrared digital cameras (SMART DX 6000, BTS Bioengineering [5]). The sampling frequency of the cameras is 340 Hz at their maximum resolution of 2048 x 1088 pixel.

For the overhead tasks, we used an ad–hoc measurement protocol composed of 10 markers placed on the upper body according to the work in [24]. The marker set is summarized in Tab. I and illustrated in Fig. 3. With respect to [24], we do not use two additional markers on the anterior superior iliac spine and four markers in the left arm (the involved subject is right–handed). A physician was involved in this study for placement of the markers on the human body and collection of the volunteer's anthropometric data and personal details.

After the calibration process of the optical systems, the participant was asked to maintain a known posture (orthostatic posture) for about 5 seconds; this allowed to acquire the reference posture of the subject's joints.

[5]https://www.btsbioengineering.com/

C. Data analysis

The markers positions during the task execution were reconstructed using BTS SMART Tracker software, using a protocol able to couple the marker set in Fig. 3 with a skeleton model.

Then, we imported the motion capture data into OpenSim software, in order to reconstruct the joint angles defined in Sec. III. Currently, a full model which consider all the joint angels of our interest is not yet available on OpenSim. Therefore, we used two different models: (i) *Full–Body Musculoskeletal Model* [25] and (ii) *Musculoskeletal Model of Head* [26]. The first includes 37 degrees–of–freedom (DOF), of which 7 DOF are for each upper limb; this is usually used to define the joints kinematics of the full body. The second, instead, has 6 DOF to define the joints kinematics of neck and trunk. The joints were reconstructed using the inverse kinematics capability of OpenSim. The others joints required by the RULA method were not computed. In order, the additional joints required are:

TABLE I
MARKER SET POSITION ON HUMAN BODY

Body part	Marker position	Joint position
Head	Left/Right Temporal Regions (TLR/RTR)	Midpoint between TLR and RTR
Torso	Left/Right Medial end of the Clavicle (LM/RMC)	Midpoint between LMC and RMC
Neck	7th Cervical vertebra (C7)	Midpoint between torso and C7
Left shoulder	Left Acromion (LA)	LA
Right shoulder	Right Acromion (RA)	RA
Right elbow	Right Lateral Humeral Epicondyle (RLHE), Right Medial Humeral Epicondyle (RMHE)	Midpoint between RLHE and RMHE
Right wrist	Right Radial Styloid (RRS), Right Ulnar Styloid (RUS)	Midpoint RRS and RUS
Back	Sacrum (S)	S

- wrist flexion–extension: the marker set on human body of the subject illustrated in Sec. IV-B does not include the market placed on the hand; for this reason the wrist flexion–extension is not calculated;
- wrist radial–ulnar and pronation–supination deviation, trunk axial rotation and lateral tilt, neck axial rotation and lateral bending; these angles, for the considered tasks, correspond with the rest position, as the subject performed the task in front of the working plan.

D. Results and discussion

The joint angles of our interest are plotted in Fig. 4. The first five subplots of the figure show the evolution over time of the joints related to: shoulder (flexion–extension 'α', abduction 'α' and rotation 'γ'); elbow (flexion–extension, 'δ'); trunk (flexion–extension, 'ε') reconstructed using *Full–Body Musculoskeletal Model* available in OpenSim. The sixth subplot of the figure shows the evolution over time of joint angles of the neck (flexion–extension, 'ζ', reconstructed using *Full–Body Musculoskeletal Model*. The method used in this work allows to obtain a detailed description of the tasks. Indeed, it underlines the limitation of using of the empirical methods (i.e. RULA method). For example, the first subplot of the figure (shoulder flexion–extension) shows that the corresponding angle (for both configurations) is always greater than 60 degrees. Using the empirical methods, it would be impossible to assess which of these configurations is the most heavy for the worker. Moreover, these methods do not consider the effort during the course of the activities. Indeed, always considering the same subplot, it is possible to observe that the number of leveraging in the third cycle decreases (as there is an increased effort of the subject during the execution of the task). In addition, others marks of the increased fatigue are shown in the second and third subplot (shoulder abduction and rotation). Indeed, there is a decreasing trend of the angles during the execution of the task, specially for the drilling task in the configuration 1.

The same observations related to the difficulty in discriminating different critical status between tasks can be replicated for the fourth subplot (elbow flexion-extension). The joint angle of the leveraging activity corresponds to the same degree of correctness of the gesture for the empirical methods (i.e. RULA local score = + 1). For the trunk flexion-extension, although all the tasks and configurations are classified in the same way by RULA, little different patterns are shown in the figure (fifth subplot Fig. 4, in particular for the leverage configuration 2). Finally, only for the neck flexion–extension, the RULA global score is sufficient for a good assessment of the task. Indeed, 'ζ' is constant for both task and configurations (with a low RULA global score). In this context, it is clear that the use of OpenSim can be useful to have a more appropriate evaluation of the tasks, even only in kinematic analyses.

V. CONCLUSIONS AND FUTURE WORKS

In this preliminary work we have computed the evolution of the joint angles of a human worker while performing industrial tasks, using OpenSim software. We considered the overhead tasks as 45% of the cases of MSD are due to these tasks. For measuring the kinematics associated with the tasks, we have used an optical motion capture system with a specific marker–set that covered trunk, head and upper limb of the subject. Then, for computing the joint angles we have used the OpenSim software. We have reported the evolution over time of the joint angles and we have presented a discussion of the results with classic measures as the RULA global score. This study underlines basic limitations of empirical methods (i.e. RULA method) for ergonomic assessment, expecially in: (i) discrimination of the heavy posture for the worker between different task; (ii) identification of fatigue during the activities. In order to develop a more appropriate methodology to estimate the human ergonomics in industrial activities, future developments will be centered on: (i) carrying out testing with a greater number of subjects with different sex and anthropometric characteristics; (ii) to modify the proposed marker–set in order to considered also wrist joints angles; (iii) applying the proposed approach also for different overhead industrial tasks (i.e. with workplace set in lateral side); (iv) considering joint torques and muscle activation.

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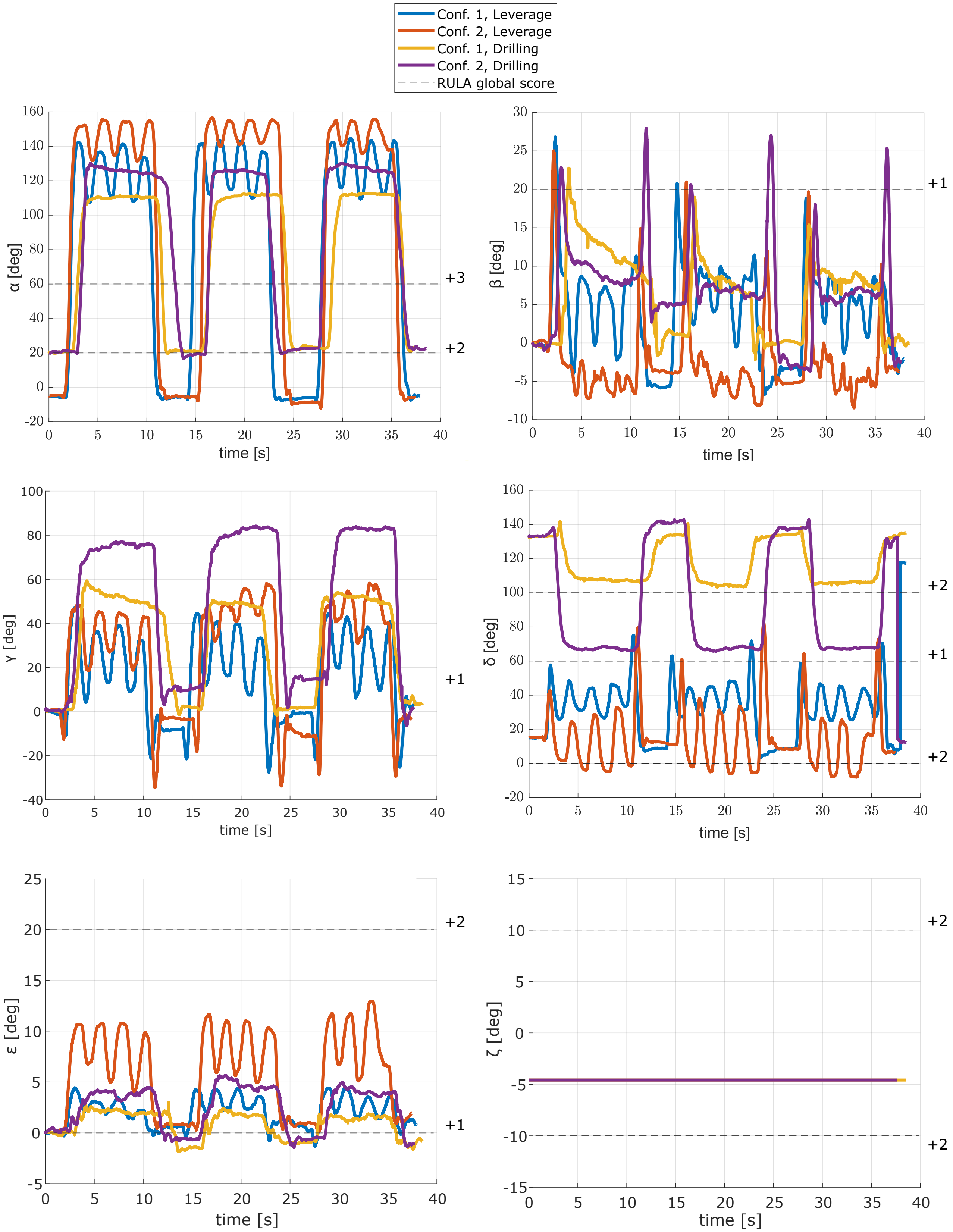

Fig. 4. Plots of the joint angles of the upper limb obtained by inverse kinematic solutions using OpenSim (”Full–Body Musculoskeletal Model”) and of the neck obtained by inverse kinematic solutions using OpenSim (”Musculoskeletal Model of Head”). The joint angles are: α: shoulder flexion–extension; β: shoulder abduction; γ: shoulder rotation; δ: elbow flexion–extension ε: trunk flexion–extension; ζ: neck flexion–extension.

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