Biomechanical–based torque reconstruction of the human shoulder joint in industrial tasks

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***Abstract*—In this work we present a study for the experimental reconstruction of the human shoulder torque in the sagittal plane, since this is usually overloaded in industrial overhead tasks. To this end, we measure the three–dimensional motion of the human upper limb while performing selected movements using an optical motion capture system. Then, using a skeleton model implemented in one of the most common software for industrial ergonomic assessment, we reconstruct the shoulder angle and torque in the sagittal plane. A possible exploitation of this reconstruction strategy is presented for active compensation of this torque. The implementation of this simple strategy in a custom developed assistive device could augment human workers in performing repetitive jobs.**

***Index Terms*—biomechanics; human motion analysis; digital human models; industrial assistive devices**

I. INTRODUCTION

In the recent years, many assistive devices have been introduced in industry to reduce the physical loading on the workers' body. Examples of applications include the use of: (i) passive systems, i.e. wearable devices which give feedback (usually vibro-tactile) on the human's body to guide him towards ergonomic postures [1]; (ii) active systems, i.e. powered robotic exoskeletons that operate in parallel with human limbs and work as human power/force amplifiers [2].

Most of existing research prototypes and commercial products have been designed using the same methodologies pursued since the beginning for the design of industrial robots [3]. This have resulted in building rigid and bulky devices which are difficult to be used in real factories. Recently, it has pointed out that accurate studies on the biomechanical aspects of human motion might help in developing wearable robots and systems which can work closely to humans [3].

Furthermore, in the context of Industry 4.0, the human–centered approach could play a growing role for custom development of many devices. This approach is common for applications going beyond the industrial scenarios, as: design of shoe sole [4], design of sports equipment [5], design of orthopaedic devices [6]–[8]. A big effort should be done in bringing these approaches in industry, in order to develop industrial workplaces tailored for workers.

Moving in the trend of human–centered biomechanics, here we propose a user–centered strategy for estimation and compensation of upper limb joint torques during the execution of industrial tasks. In particular, we are interested in studying the motion of human workers in automotive industrial workplaces, where overhead tasks are the most common. Since the shoulder load in the sagittal plane is the most overloaded for overhead tasks, we estimate the shoulder torque in this plane and, for this, we propose a possible compensation strategy. In this context, the paper presents a possible strategy for integration of measurement data into biomechanical models, with the objective to design of adaptive mechanical systems. Being focused on the industrial field, we choose to use tools and instruments which are common for industrial ergonomics.

First, we select the industrial tasks of interests. Then, we execute in laboratory settings the industrial tasks, and we track the human movements using an optical motion capture system. From the three-dimensional motion of multiple markers attached to the subjects' body as landmarks, we reconstruct the joints angles, velocities and accelerations. In this phase, a particular physically simulated skeleton model is used, where the individual link parameters are measured by a physician. Then, we compute the joint torques using the 3D Static Strength Prediction Program (3DSSPP) software available in Siemens Tecnomatix Jack$^{\text{TM}}$. Finally, a simple torque feedforward compensator is designed and validated through simulation studies. A qualitative picture of the proposed methodology involving task acquisition, movement reconstruction and feedforward compensator is given in Fig. 1.

The paper is organized as follows. Section II contains a brief review of the technologies used for human motion reconstruction and estimation of joint angles/torques using digital human models. Section III describes the experimental tasks and the related data acquisition. Section IV presents the data processing and preliminary results. Finally, Section V gives preliminary conclusions.

II. RELATED WORK

The section allows to understand the guideline follows in this work for the choice of the technology for human motion reconstruction and for the estimation of joint angles/torques. The presented framework of the related works give an overview on: (1) the best available technologies used for human motion reconstruction; (2) the main characteristics of digital human models (DHM) used for estimation of joint angles/torques using.

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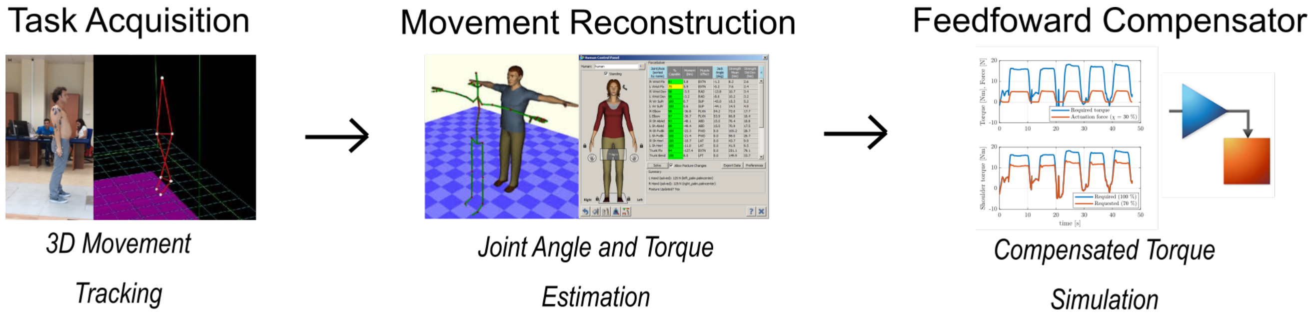

Fig. 1. A qualitative picture of the flow chart followed in this work: task acquisition, movement reconstruction and feedforward compensator.

1) Technologies for human motion reconstruction: The most common technologies for kinematic reconstruction of human motion belong to the groups of: wearable system and optical system.

Wearable sensors used for human motion analysis include: accelerometers, gyroscopes, magnetometer and combination of them (i.e. inertial sensors [9]–[11]). They allow to estimate the 3D trajectory of human body by numerical time–integration. However, the accuracy of this numerical integration is hindered by errors that grow over time due to gyroscope bias drift [12]. The gold examples of wearable systems for human motion reconstruction are the inertial–based suits [13].

Optical systems are divided into markerless and marker–based systems. In first category, a very well known sensor is the Microsoft Kinect, that represents a low-cost instrument for human motion analysis. However, the literature underlines how Kinect is valid only for some spatio–temporal gait parameters [14]. As a matter of fact, the joint trajectories show poor validity and large errors. The gold standard technology is represented by optical system based on markers placed on human body [15], [16]. They guarantee an accurate capturing of human movement. Although this technology allows the acquisition only in a limited volume of calibration (i.e. indoor space), it represent the current most powerful technology for accurate human motion acquisition.

2) Digital human models: Digital human models (or skeleton models or virtual manikins) represent the human body as a complex system composed by multiple segments connected through kinematic joints under the hypothesis of rigid bodies. The most common DHM allow a customization of their skeleton starting from anthropometric measurement and/or optical acquisition of the human body [17]. Then, through the constraint with real markers trajectories, the human tasks are reproduced. The relative angular displacement between two consecutive human links allow to calculate the joint angles (for example using Euler angles).

In order to estimate joint torque, the inverse dynamic model represents the best solution. It allows the computations of the net forces and moments at every stage of the task through the classical dynamical equations of motion. However, when velocities are not high, static models can be used as well [18]. As a matter of fact, when the human task is composed by slow movements, static analysis tools provide good approximation of the actual loads acting on the human musculoskeletal system [19]. Currently, in the context of industrial ergonomics, most of industry–oriented DHM software does not implement a true inverse dynamic model, but rather they perform ergonomics assessment using static models.

TABLE I
OVERHEAD TASKS

No	Name	Tool	Tool weight [g]
1	Screwing	Screwdriver	40
2	Leverage 1	Wrench	85
3	Leverage 2	Wrench	690
4	Drilling	Drill	2000

III. DATA ACQUISITION

A. Choice of the experimental industrial tasks

In this work we are focused in the automotive industry. In this field, *overhead tasks* involving the use of working tools have been marked as one of the most stressful for the workers [20]. Indeed, in this scenario, human operators are obliged to held an uncomfortable posture for extended periods of time.

In collaboration with our industrial partner, we select four overhead tasks involving the use of different tools with total weights spanning from 40 g to 2000 g. The selected tasks are reported in Table I. All the tasks foresee first a phase of working when the human effectively perform the industrial tasks (10 s for Task 1; 7 s for Task 2 and 3; 5 s for Task 4), then a phase of reset when the human has only the tool in hand (4 s for Task 1, 2 and 4; 3 s for Task 4).

B. Experimental setup and measurement protocol

The experiments were conducted at ERGOS Lab, University of Naples Federico II. To measure the kinematics of human motion, we used an optical motion capture system composed by ten infrared digital cameras (SMART DX 6000, BTS Bioengineering). Their sampling frequency is 340 Hz at their maximum resolution of 2048x1088 pixel. The experiments involved one male, healthy volunteer (age: 28 years; mass: 83 kg; height: 1.72 m). A physician collected the informed consent from volunteer as well as his personal details, anthropometric characteristics and guarantee the correct markers placement. The markers were placed according to the Churchill Livingstone convention [21]. The whole marker set

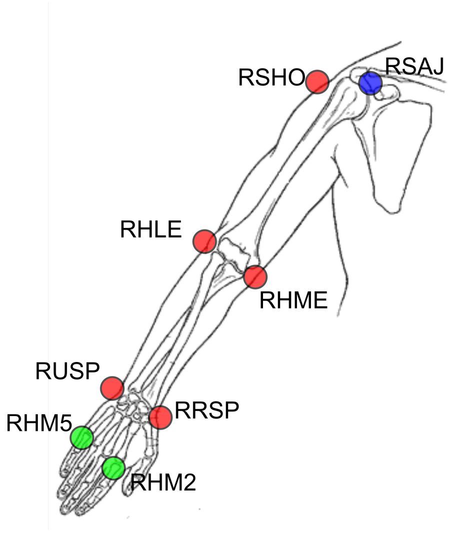

Fig. 2. Marker set placement on the subject's body: RSAJ: Right Scapula–Acromioclavicular Joint; RSHO: Right Shoulder; RHLE and RHME: Right Lateral Epicondyle of Homerus and Right Medial Epicondyle of Homerus; RRSP and RUSP: Right Radius Styloid Process and Right Ulna Styloid Process; RHM5 and RHM2: Right 5^{th} and 2^{nd} Head of Metacarpal.

(composed by 8 markers) placed on the subject's body is given in Figure 2. At the beginning of the test, the participant was asked to maintain an orthostatic position for about 10 seconds. This acquisition (called *standing*) was to set a reference posture for his joint angles. Then, three trials for each test in Table I were conducted. Each trial consisted in five work cycles. A work cycle is defined as a two phase period split in an overhead holding phase alternated to a resting phase. The ratio between holding and resting has been chosen differently according to the tools weight ensuring a duty cycle ranging in a [60-75]% interval. The order in which the tasks were performed was chosen as to ensure that the human involved in this study could not get used to an increasing (or decreasing) variation of the employed tools weight.

IV. DATA PROCESSING

A. Human kinematic reconstruction

The spatial reconstruction of the markers movement over time was done via BTS SMART Tracker software using a protocol able to couple the marker set in Fig. 2 with a skeleton model. Then, the motion capture data corresponding to the standing, reset and working acquisitions were imported into Siemens Tecnomatix Jack^{TM} through an open data exchange format (C3D). The data exchange process also implied the re–sampling of the signal from 340 Hz to 30 Hz.

A digital human with the same anthropometric characteristics of the volunteer was created in Jack using the v6.1 segmented male skeleton model. The full manikin is made up of 70 segments, 69 joints and 135 degrees of freedom (with the upper limb, under investigation, made up of 18 segments, 17 joints and 23 degrees–of–freedom). This skeleton was created to match the height of the subject and it was carefully resized to match his trunk and arm to forearm ratio. The reference posture for the virtual manikin was set on the basis of the standing posture data. Virtual markers were positioned and bound onto the manikin and the correct correspondence between real sites and sites referenced by the chosen protocols was later verified. The constraint between the real and virtual marker positions allow the generation of the manikin animation. This animation represents the frame data collection for the assessment of joint angle on which the Static Strength Prediction tool operates, as described below.

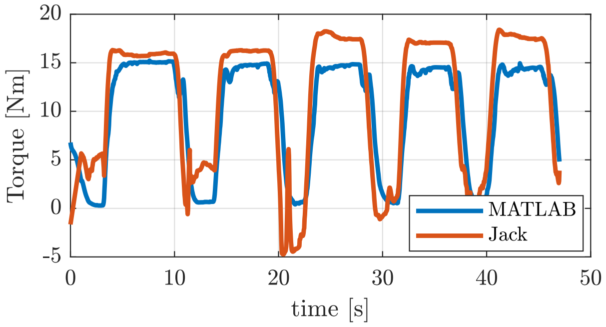

Fig. 3. Comparison of shoulder torques reconstructed in Jack and MATLAB.

B. Torque estimation

The objective of this phase is estimating the torques acting on the shoulder of the virtual manikin. To this end, we use the 3D Static Strength Prediction Program (3DSSPP) developed by the University of Michigan [22] and included in Siemens Tecnomatix Jack^{TM}. This tool neglects any inertial effects and uses a up–to–down approach for the solution. Indeed, the joint torques are computed starting from the external applied forces. Since during the tasks different tools with different weights have been employed, we simulate the weight of the tools as an external force applied to the center palm of the right hand of the skeleton. The static analysis was performed only for the fourth overhead task, the drilling test. The output of this analysis is the computation of the shoulder joint torque in the sagittal plane.

In order to confirm the reliability of using 3DSSPP for static reconstruction, we develop a simple model using MATLAB Simulink Simscape (which has dynamic capabilities). The model simulates the whole arm as a double pendulum system, where the upper and forearm links are modeled as rigid bodies with squared cross section, sized according to a study on the subject's arm. The density of the rigid bodies was assigned to match the 50^{th} percentile of a human body arm. We apply to this model the same joint angles applied to the Jack model, as resulting from the kinematic reconstruction. The comparison of the two reconstructed torques for the shoulder in the sagittal plane is given in Fig. 3. The models can be considered to be similar in a 20% confidence interval.

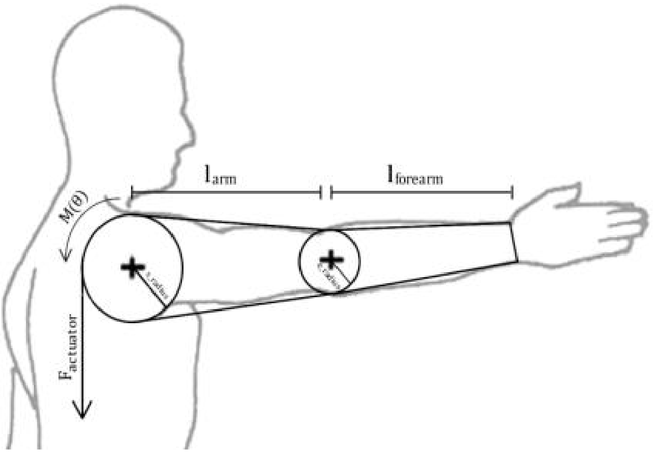

Fig. 4. Compensation model

C. Torque compensation

The objective of this part is to find a suitable strategy for (partially) compensating the torques acting on the considered joint. In this way, the workload from the operator side can be reduced. We are assuming that the overhead tasks are constrained in the sagittal plane; therefore, following the model given in Fig. 4, our idea is to compensate the shoulder's torque by applying a linear force F_a acting on the rear part of the shoulder as

$$F_a = \frac{\chi \theta_n(t) M_{max}}{r} \tag{1}$$

where χ is the compensation factor (between 0% and 100%); $\theta_n(t)$ is the joint angle of the shoulder in the sagittal plane, normalized over a [0–100] range; M_{max} is the peak value of the estimated shoulder torque; r is the shoulder radius, or the distance where the linear compensation will be exerted.

Figure 5 shows preliminary results on the compensation strategy. In the top part, we can see the compensation function in (1) for $\chi = 30\%$ plotted on top of the shoulder torque required for the execution of the movement (as it has been reconstructed). When the upper arm is in standing position ($\theta = 0$), there is no active compensation. This means that the compensation strategy does not interfere with the natural movements of the operator. By subtracting the compensation torque from the reconstructed shoulder torque, we obtain the effective torque requested to the operator (70 % in this case) for performing the drilling task.

Notice that (1) requires the real–time measure of the sole joint angle of the shoulder (which can be estimated even with a simple camera parallel to the sagittal plane); indeed, the value of the shoulder radius is pre–measured, while the peak value of the shoulder torque is pre–computed offline using a procedure as the one in Sec. IV-B for a test overhead movement (this is not limiting since a certain regularity of the task is observed from data).

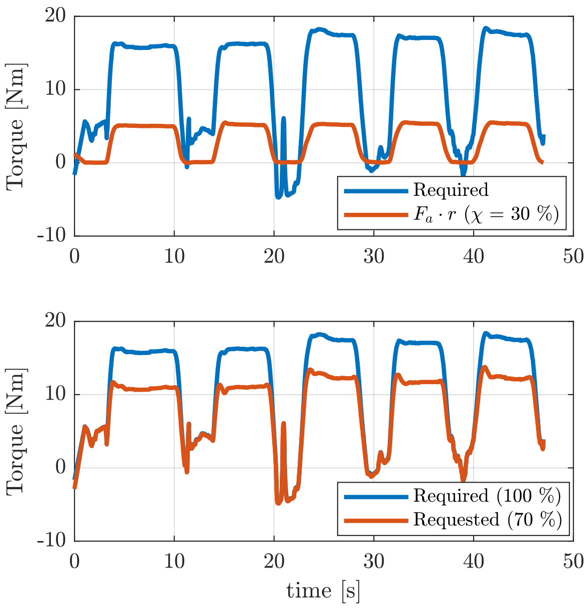

Fig. 5. Compensation results

V. CONCLUSIONS

In this short paper we present a biomechanical strategy for shoulder torque estimation and compensation during overhead industrial tasks. For measuring the kinematics associated with the tasks, we use an optical motion capture system with markers placed on the subject's body. Then, for joint angles and torque estimation we use an industry–oriented software for digital human modeling. Finally, we propose an initial torque compensation strategy. This preliminary results show that the approach for torque reconstruction of the human shoulder joint could be considered sufficiently accurated for industrial settings, and that the compensation strategy could be further investigated as its implementation is simple. Furthermore, future development could be based on: (i) applying this strategy to a dynamic skeleton model (i.e. OpenSim); (i) carrying out testing with greater number of persons with different sex and anthropometric characteristics; (iii) applying the proposed strategy also for different industrial task (i.e. pick up task).

The paper shows the integration of measurement data into models could be useful for the design of adaptive mechanical systems. Indeed, this work underlines that accurate studies on the biomechanics of human motion based on optical motion capture metrology systems could have impact in the development of assistive devices for reducing the operators' workload for selected tasks.

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