Quantifying the contribution of single joint kinematics to the overall ergonomic discomfort

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***Abstract*—Work-related musculoskeletal disorders (WMSDs) represent one of the major issues concerning the occupational safety and health of workers. Thus, a reliable evaluation of workers' exposure to the risk factors that may contribute to WMSDs development is mandatory, above all, within an industrial context. At present, standard synthetic indices are widely used in this frame, presenting – however - several limitations due to poor reliability and time efficiency. The aim of this work was to investigate the contribution of the displacement quantified for each single joint during the execution of simple reaching tasks, to the overall discomfort of the worker evaluated by means of standard observational methods.**

Forty-five healthy volunteers were included in the analysis; each subject was asked to reach and rotate 2 spheres placed on a custom-made rack in standardized positions, i.e., above the head and one at floor level at centre side. Whole-body kinematics was acquired via a system based on wearable inertial measurement units. Standard ergonomic scales including RULA (Rapid Upper Limb Assessment), REBA (Rapid Entire Body Assessment), and MMGA (Method for Movement and Gesture Assessment), were assessed for each subject and each sphere position. Moreover, a quantitative index based on actual joint kinematics, i.e., W_1 index, was computed for each joint angle involved in the task. Correlation analysis was performed for W_1 relative to each joint with respect to RULA, REBA, and MMGA scores.

Considering REBA and MMGA scores, the most comfortable reaching areas were the ones in which the sphere was positioned at the top; in contrast, the lowest positions evidenced the most increased discomfort indexes. The RULA did not result sensitive to the different positions, while REBA and MMGA seemed to be more influenced by the range of motion of the lower limb joint angles than the upper limb ones.

This study underlines the necessity to focus on multiple potential contributors to WMSDs and underlines the importance of subject-specific approaches toward risk assessment by exploiting quantitative measurements and wearable technologies, which indeed represent key enabling approaches even in consideration of the novel "Industry 5.0" perspective.

***Keywords*—Ergonomics assessment, wearable technologies, kinematic monitoring, risk assessment, standard scales, RULA, REBA, MMGA.**

I. Introduction

Work-related musculoskeletal disorders (WMSDs) have been widely reported to be a leading cause of sick leave in many occupational contexts [1]. Indeed, within working environments, it is still common to suffer from repetitive arm movements, and awkward postures are widely adopted despite very recent improvements also due to the introduction of several enabling technologies, including exoskeletons and robots [2]. Indeed, within the actual context defined by "Industry 4.0", work intensity has been growing because of the presence of "hybrid" manufacturing lines which can involve workers in increasingly complex activities. For these reasons, very recently, "Industry 5.0" human-centric approach has been proposed also to mitigate these problems and promote the concepts of overall occupational well-being.

From a general perspective, health and welfare costs for workers must be considered when applying policies aimed at minimizing WMSDs risks. At present, to prevent WMSDs, the best practice is to properly evaluate the exposure to risk factors of a class of workers in a defined working environment during the realization of specific tasks characterizing their working shift; following this analysis it is mandatory to plan ergonomic interventions, as – for instance - a workplace redesign [3]. In this picture, a large number of observational methods, which are widely used in industry, have been presented in the last decades, most of which involve direct visual observation of workers during their activities [4,5]; this approach supports the need to assess the risk of developing WMSDs, which led to the definition of ergonomic scales addressing overall discomfort. In particular, RULA (Rapid Upper Limb Assessment) [6], and REBA (Rapid Entire Body Assessment)[7] represent the main applied methods during ergonomic risk assessment. On the other hand, these two scales present several limitations and have the main disadvantage to require a field expert who performs a time-consuming analysis of the postures.

Over the years some progress has been made to overcome the limits of these methods, leading - for example - to the definition of the MMGA (Method for Movement and Gesture Assessment) [8] and the introduction of wearable technologies, as inertial measurement units (IMUs) which allow for quantitative assessment [9].

However, the use of discrete parameters could be a limitation considering the inherent variability that exists in the ways individuals can complete a specific working task; in fact, most of the movements we perform during daily life activities involve different muscles and multiple joint coordination.

Recently, Lorenzini *et al*. designed a multi-index framework based on kinematic and dynamic parameters estimated via wearable technologies [9]. In particular, the authors proposed a kinematic-based displacement index (W_1) for each joint and degrees of freedom. However, the authors did not provide cues concerning possible relations between standard assessment methodologies and joint-specific metrics.

Therefore, this work aimed at investigating the contribution of the displacement quantified for each single joint (W_1)

during the execution of simple reaching tasks, to the overall discomfort of the worker evaluated by means of standard observational methods and scores. In fact, we hypothesized that W_1 represented a paradigmatic kinematic index able to better highlight the multi-factorial aspects that affect the overall discomfort of the worker and – vice versa – we focused on the need to introduce specific quantitative and subject-specific approaches able to better characterize the occupational risks and, thence, guide the mitigating strategies.

II. Materials and methods

A. Participants

Forty-five healthy volunteers (33 females, 12 males, mean age 25.1 years old) were enrolled in the study. All the subjects reported no previous history of neurological disorders or recent orthopedic injuries. All subjects were right-handed according to the Edinburgh Handedness Inventory [10]. All the subjects were instructed with respect to the assessment procedure and signed informed consent. The study was approved by the local institutional review board (Comitato Etico dell' Area Vasta Emilia Nord, 10084, 12.03.2018).

B. Experimental setup and Testing procedure

Subjects were asked to perform motor tasks which consists of reaching and manipulating 2 soft spheres (6 cm diameter) placed on a 2x1 meters rack, adapting the experimental paradigm proposed by Andreoni et al. [8]. In particular, the 2 spheres were positioned according to the anthropometric measures of the subject and centered on the midline; the one in the lower position was placed 6 cm above the floor, whereas the one in the top position was moved in correspondence to the participant's height plus 10 cm. The subjects stand still in front of the rack with the feet behind a reference cross placed considering the length of the forearm plus 30 cm, to make the task more challenging. Each movement started from a static standing position with the arms by their side and the subject was asked to perform the task without crossing the reference line and without lifting their feet completely off the ground. From the starting position, participants reach and grasp the sphere addressing the manipulation of each sphere, i.e., three times clockwise rotations with the right hand. The task was repeated five times for each position of the spheres (i.e. the upper and lower ones). The experimental setup and task execution are reported in Figure 1.

C. Motion tracking

Whole-body kinematics was acquired by using a full-body motion tracking system based on IMUs (MVN Link and Biomech Awinda, XSens, The Netherlands). The motion trackers were positioned within the suit according to the protocol required by the manufacturer; in particular, 17 sensors were positioned on the subject to capture the movement of the following 23 body segments, which included the head, neck, eighth and tenth thoracic vertebra, third and fifth lumbar vertebra, right and left shoulder, right and left arm, right and left forearm, right and left hand, pelvis, right and left thigh, right and left shank, right and left foot, and right and left forefoot. Before starting the recording session, a calibration procedure was performed to align the motion trackers to the anatomical segments of the subject. The movement were acquired by using a sampling frequency of 240 Hz.

D. Data analysis

Data acquired by IMUs were first exported by using the Xsens MVN-Analyze software (XSens, The Netherlands). From the kinematic variables provided by the software, we selected three-dimensional joint angles which were exported via custom routines developed in a numerical computing environment (Matlab2018a; MathWorks Inc.). Before additional data processing, the start and end frames for each trial were determined. In particular, we focused only on the reaching phase which was segmented according to the tangential velocity of the hand [11]; the temporal boundaries of the reaching phase were identified as the times at which the hand velocity surpasses and returns below 5% of the peak velocity (reaching start and end, respectively).

Once defined the overall repetition, RULA and REBA indices were estimated and MMGA scores were calculated for each subject, each sphere position, and each trial and then averaged among trials. Moreover, the kinematic-based displacement index W_1 was computed for paradigmatic joints, including pelvis-trunk, right shoulder, right elbow, right wrist, right and left hips, right and left knees, and right and left ankle; W_1 was averaged among trials as well. We decided to not consider the joint angles relative to the left upper limb since all subjects were right-handed.

To evaluate the difference between lower and upper conditions, paired t-tests were conducted for RULA, REBA, and MMGA. Pearson's correlation analysis was performed for the values of W_1 relative to each joint with respect to the obtained, REBA, and MMGA scores, and Spearman correlation with RULA scores to assess their sensitivity with respect to the contribution of each individual joint.

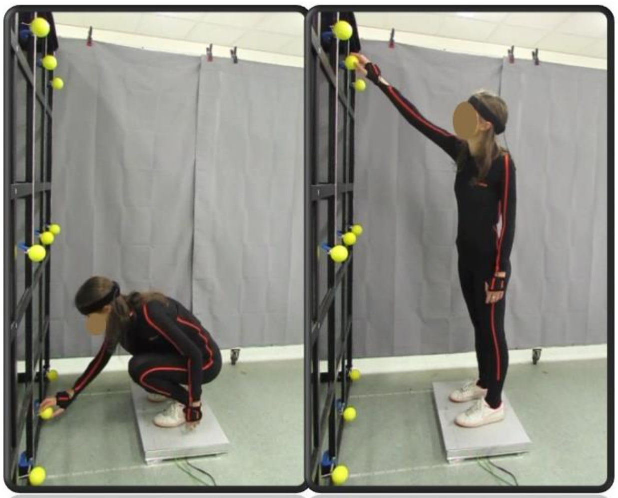

Fig. 1: Experimental setup; spheres on right, left sides and in the middle line were not used for this study.

III. Results and discussions

Concerning the lowest and highest positions, the average scores of RULA were 6.08 (±0.56) and 5.97 (±0.33) ($t(44) = 1.56$, $p = 0.12$), whereas focusing on REBA we obtained a score of 10.04 (±0.72) and 7.46 (±0.71) ($t(44) = 22.73$, $p < 0.01$), respectively; from the analysis of

MMGA, the score was 424.75 (±44.62) for the lower and 190.42 (±21.72) for the highest position ($t(44) = 39.8$, $p < 0.01$).

Considering both REBA and MMGA scores, the reaching areas presenting less discomfort were the ones in which the sphere was positioned at the highest level; on the other hand, the lowest position evidenced the most increased discomfort indexes. Surprisingly, the RULA index did not highlight any difference between the tasks devoted to reaching the sphere positioned at the highest level with respect to that placed at the lowest one, highlighting a lack of sensitivity towards this kind of task.

Focusing on the correlation analysis, the main results are reported in Table 1.

TABLE 1 – SPEARMAN AND PEARSON'S CORRELATION COEFFICIENT AMONG W1 RELATIVE TO EACH JOINT WITH RESPECT TO RULA, REBA, AND MMGA SCORES. (*) INDICATES P < 0.05.

W_1	*RULA*	*REBA*	*MMGA*
Pelvis_trunk bend	*0,03*	*-0.64**	*-0.64**
Pelvis_trunk rot	*0,16*	*0.37**	*0.51**
Pelvis-trunk tilt	*0,29**	*0.92**	*0.95**
RShoulder Ab	*0,00*	*-0.72**	*-0.75**
RShoulder Rot	*-0,09*	*-0.76**	*-0.86**
RShoulder Flex	*-0,06*	*-0.61**	*-0.76**
RElbow prono	*0,02*	*0.11*	*0.10*
RElbow Flex	*-0,18*	*-0.79**	*-0.87**
RWrist Flex	*0,19*	*0.61**	*0.63**
RHip Ab	*0,18*	*0.72**	*0.85**
RHip Rot	*0,30**	*0.65**	*0.74**
RHip Flex	*0,16*	*0.90**	*0.96**
RKnee Flex	*0,13*	*0.89**	*0.97**
RAnkleFlex	*0,23**	*0.86**	*0.91**
LHip Ab	*0,21**	*0.71**	*0.81**
LHip Rot	*0,20**	*0.70**	*0.77**
LHip Flex	*0,17*	*0.90**	*0.96**
LKnee Flex	*0,06*	*0.88**	*0.96**
LAnkleFlex	*0,17*	*0.87**	*0.91**

In this frame, the RULA index significantly correlate with any W_1 of trunk bending, right and left hip rotation, right ankle flexion and left hip abduction. However, the correlation coefficient does not exceed 0.30 ,further underling the lack of sensitivity of this assessment method with respect to these specific tasks. On the other hand, both REBA and MMGA negatively correlate with trunk bending, all shoulder rotations, and elbow flexion ($r < -0.65$, $p < 0.01$); further, both indices positively correlate with trunk tilt and all rotations of the lower limbs' joint angles ($r > 0.65$, $p < 0.01$).

As we expected, and as it was confirmed by the analysis of W_1, the movements toward the highest vs lowest positions recruited body segments differently. Figure 2 shows, as a paradigmatic example, the difference in terms of joint angles curves. It is possible to notice that participants expressed higher shoulder flexion in movement toward the upside with respect to the ones in the low side. On the contrary, higher grades of knee flexion characterize the movement in the lower part of the rack. Finally, RULA seemed to be not sensitive to the different positions, whereas REBA and MMGA seem to be more influenced by the range of motion of the lower limbs' joint angles than the upper limbs' ones.

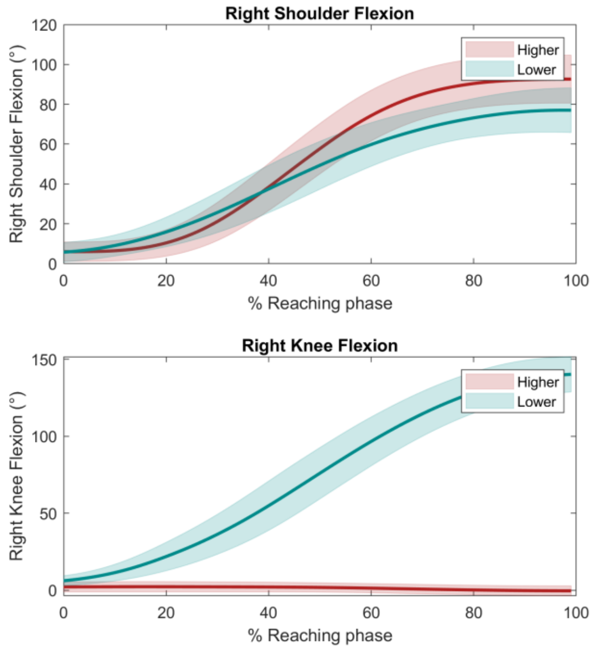

Fig. 2: Mean and standard deviation among subject of the normalized joint angle curves. Right shoulder flexion curves relative to task in the higher and lower position is depicted on the top. Right knee flexion is depicted in the bottom of the figure.

IV. CONCLUSION

The aim of this work was to investigate the contribution of each single joint, in terms of overall joint displacement (W_1) to the overall discomfort of the worker during the execution of manipulative tasks evaluated by means of standard observational methods and scores. In fact, we focused on the need for assessing which standard ergonomic index is more sensitive to the variations of the position of individual body districts.

From the main findings obtained in this study emerged that RULA index was indeed not sensitive to the different tasks required to reach the sphere placed at different positions; on the other hands both REBA and MMGA seemed to be more suitable to underline the ergonomic difference emerging from the two tasks. The reaching areas presenting less discomfort were the ones in which the sphere was positioned at the highest level, while the lowest position evidenced the most increased discomfort indexes.

Moreover, the REBA and MMGA seem to be mainly influenced by the range of motion of the lower limb joint angles than the upper limb ones.

Further studies should be conducted considering different tasks combining different body positions and applying different loads.

These findings suggest the need to focus on multiple potential contributors to WMSDs and underline the importance of subject-specific approaches toward risk assessment by exploiting quantitative measurements and wearable technologies, which indeed represent key enabling approaches within "Industry 5.0" perspective.

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