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Original Research Article

A Predictive Model to Quantify Joint Torques and Support Reaction Forces When Using a Smartphone While Sitting with and Without Support: Toward a Risk Scale Proposition to Prevent Musculoskeletal Disorders

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ABSTRACT

New portable technologies such as smartphones are developing in a very important way and their use rate is increasing every year. Faced with this growth, it is relevant to consider the risks of developing musculoskeletal disorders related to their increasing utilization. The objective of this study was twofold: 1) to propose a predictive model of the upper body joint angles, torques and reaction forces during smartphone interaction in seated position based on subject's anthropometric data, environmental conditions and interaction strategies in the sagittal plane; 2) to propose risk scales for joint torques provided by the model and which could be integrated with information on posture as part of the musculoskeletal disorders prevention. One of the original aspects of the predictive model was to consider postural strategies between the trunk and the neck during smartphone interaction. The validation was carried out by comparing experimental data collected from 12 subjects who had to perform texting and web browsing task while sitting on a chair with or without support and the data simulated by the model under the same conditions. The results showed a satisfactory ability of the model to reproduce the subjects' posture. However, more marked differences were observed for reaction forces and for shoulder and elbow flexion when trunk flexion was significant. A validity domain for each parameter was computed for different seat and support heights according to the subjects' body mass index. From these data, joint torques risk scales have been constructed, to characterize the risks incurred by the users.

Keywords: Predictive Model, Musculoskeletal disorders, Risk scale, Sitting, Posture, Torque/Force.

INTRODUCTION

Prevention of musculoskeletal disorders (MSDs) has an important research area for many years. The consequences on health operators induce a high rate of absenteeism with a significant additional cost which amounts to millions of hours of work stoppages. From a financial point of view, this translates into direct and indirect costs of several million euros for the health systems of the countries concerned (1). The international literature has studied this problem in depth through the understanding and analysis of work or leisure postures in order to assess the potential risks of (MSDs). Many parameters have been studied such as working positions/postures adopted (2), repetitiveness of the task (3, 4), duration (5, 6), load to be moved (7) and MSDs . The risk assessment is often done by ergonomic tools that provide a score representing the risk of MSDs such as the Rapid Upper Limb Assessment - RULA (8), the postural Loading on the Upper Body Assessment - LUBA (9), the Rapid Entire Body Assessment - REBA (10), or the Novel Ergonomic Postural Assessment Method - NERPA (11).

These works in ergonomics uses questionnaires, EMGs, accelerometry and more rarely optoelectronic systems to study posture and muscle load. Few of these works exploit the quantification of unobservable variables such as joint couples, intersegmental efforts or powers. However in biomechanics, models are developed to characterize the posture and / or to quantify the torques and the reaction forces. Many models have been proposed in the literature to study postural control (12), sitting posture subjected to vibrations (13) or vehicle entry / exit (14). This model-based approach is almost non-existent in ergonomics, particularly in the interaction tasks study with a smartphone. This approach would however be very interesting since it involves tasks carried out throughout the day (3.7 hours of use per day (15)) in various environments, in different positions and with users presenting different morphological characteristics. It would make it possible to avoid experimentation that are costly financially and time-consuming.

Predictive models make it easier to study all conditions of use through families of positions, taking into account individual variability through their BMI. It is recognized in the literature that the most frequent positions are sitting and standing (16). It is also known that 90% of the time spent using a smartphone is dedicated to texting and web browsing tasks (17). In this context, a predictive evaluation tool for posture, joint torques and support reaction forces during interaction with a smartphone in a seated position will be proposed. The presence of a support will also be considered in the model because it is a situation often encountered and which presents several advantages on the ergonomic level. Such a modelling tool makes it possible to characterize the posture and quantify the unobservable variables (torques and efforts) without the need for experimental measurements. Moreover, it allows recommendations to be proposed and, in the long term, the risks of MSDs to be assessed.

The first objective was to propose a predictive model for two of the most common tasks performed using a smartphone. The user's posture definition taking into accounts the support efforts and torques according to the environmental characteristics, i.e. the support and sitting heights. One original aspects of the model presented is to take into account the morphological characteristics of the subject, i.e. size and weight. The second objective was to generalize the data set quantified by the predictive model for a large panel of subject morphologies and a set of environmental conditions for the two interaction tasks in both supported and unsupported situations. In a first step, all these data allowed to define a validity domain for each parameter (joint, torque and reaction forces). The aim was to evaluate the risks of MSDs and to propose recommendations. In a second step, based on these data and on work in the literature, risk scales for joint torques and reaction forces would be proposed.

MATERIALS & METHODS

Using smartphones while sitting is one of the most common situations both in everyday life, at work or in leisure (16). The neck, trunk and upper limb are the most stressed parts of the body. It has been widely shown in the literature that these joints are mainly used in flexion (in sagittal plan). The presence of a support has also been identified as beneficial from an ergonomic risk point of view (18, 19). In this context, Merbah et al. (20) reported the existence of postural strategy when interacting with a seated smartphone while texting and web browsing. An originality of this work was to consider these strategies in design of the proposed model.

In first time, the model computes the joint angles of the trunk, neck and shoulder, elbow and wrist. This essential step is recognized in the literature as predominant in determining the level of risk of musculoskeletal disorders (8, 9, 11). In addition, the model incorporates torques computation because they macroscopically represent the muscle activity necessary to maintain the posture (21). Because reaction forces are important information for the posture stability and can be a source of discomfort and pain when the loads or the duration of support become too high, they were computed by the model (22, 23). All of these data are important to establish recommendations and to help assess the consequences of strain and high torque in MSDs prevention.

Model development

Two conditions have been considered: seated on a chair with a table as upper limb support (ST condition, Figure 1A, left panel) and seated on a chair without any support (SWT condition, Figure 1A, right panel). Figure 1B provides the model functional diagram. The predictive model was programmed under Matlab (The Mathworks, Inc., Natick, MA) and composed of three modules:

1. *A resolution module of the body geometry* (Figure 1A, Top panel) including the head, trunk, arms, forearms, hands. From the seating height (and the support height if it is present, respectively $H_{Support}$ and H_{Seat}, Figure 1A) and subject height, all the joint centers have been computed in the sagittal plane. Each segment length has been obtained using Plagenhoef's anthropometric tables (24). All the results were expressed in the global coordinate system $R\,(A, \vec{x}, \vec{y})$. Then, the relative joint angles were quantified by an iterative geometric resolution segment by segment starting from the trunk (point A, origin of the global coordinate system) towards the extremities, i.e. head and hand, in agreement with the International Society of Biomechanics (ISB) recommendations (25). The model takes into account the angles of the trunk, neck, shoulders, elbows and wrists. In this work, strategies were identified from measurements of neck and trunk flexions as well as the head-smartphone distance from Merbah et al. (20). Thus, these three parameters have been integrated to compute the model geometry.

In addition, coefficients were applied to the lengths of the arm and forearm to take into account the movements existing in the other planes. Thus, for the condition with support (ST), a coefficient of 0.85 was assigned to the arm length in order to compensate the presence of abduction in the frontal plane. A coefficient of 0.7 was applied to the forearm length to compensate the medial shoulder rotation in the horizontal plane. For the no-support condition (SWT), only a coefficient of 0.8 was applied for the forearm length to compensate the medial shoulder rotation in horizontal plane. The smartphone position was defined from the face-to-smartphone distance reported by the work of Merbah et al. (26) for each strategy (Figure 1A). The gaze is itself positioned in relation to the posterior segment of the head and to the size of the head. An angle of 20° relative to the gaze axis (perpendicular to the head) was applied to define the top of the smartphone on the basis of classic recommendations in ergonomics when using a screen (27). On the other hand, the lower part of the smartphone was positioned in the center of the hand segment with an average angle of 22° according to the work of Merbah et al. (20). The elbow position was obtained by minimizing the distance between the two points computed from the arm and forearm lengths.

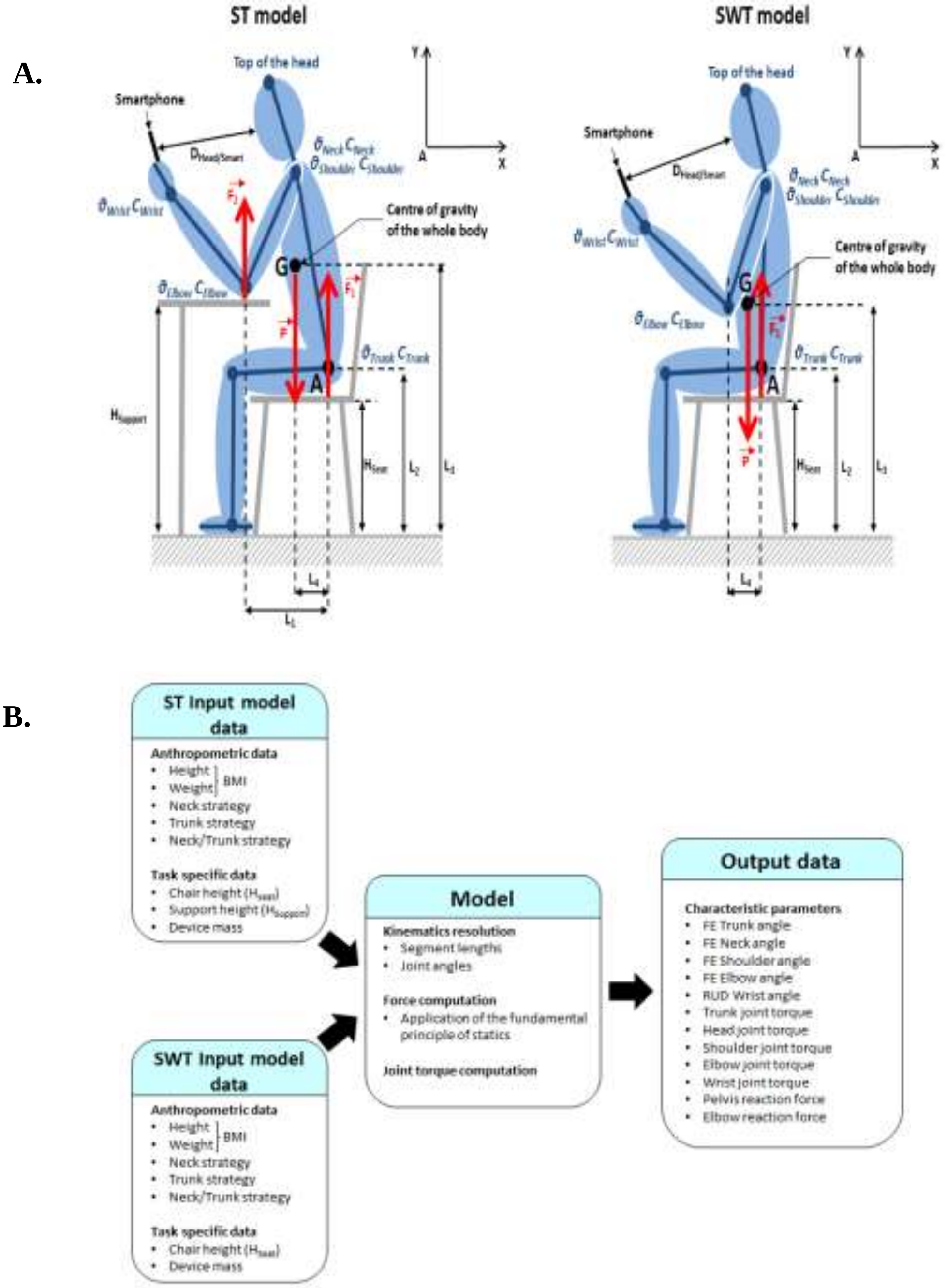

Figure 1: Model structure. $H_{Support}$ refers to the table height and H_{seat} refers to the seat height.

2. *A reaction force computation module*. The second block allows the reaction forces computation (elbows and pelvis reaction force) using the fundamental principle of statics. The first equation evaluates pelvis reaction force (F_1, Point A, Figure 1A,):

$$F_1 = \frac{((L_4 - L_1) * P)}{L_1} \qquad (1)$$

where: P was the subject's weight (N), L_1 is the distance between the support under the elbow (B) and the seat reaction in A (x-axis), L_4 is the distance between A and the G of the upper body (x axis).

The second equation is use in the situation with support (ST). It allows estimating the reaction force F_2 under the elbow resting on the table:

$$F_2 = P - F_1 = \frac{P L_4}{L_1} \qquad (2)$$

where: P is the subject's weight, F_1 is the pelvis reaction force, L_1 is the distance between the support under the elbow (B) and the seat reaction in A (x-axis), L_4 is the distance between A and G of the upper body (x axis).

3. The last *module iteratively computes the torques* from the thoracolumbar to the wrist. The relative masses as well as the segmental centers of mass were determined from the anthropometric tables of Winter (28).

The model outputs the parameters relating to each module: the joint angles (5) and joint torques (5) in the sagittal plane for the neck, trunk, shoulders, elbows, wrists, as well as the pelvis and elbow (if support was present) reaction forces for a total of 11 (SWT) or 12 (ST) variables.

Model validation

Twelve subjects with different anthropometric characteristics (mean height: 1.76 ± 0.14 m; mean weight: 80.33 ± 29.95 kg) participated in model evaluation. None of them had any disorders or pathologies related to the musculoskeletal system. Each subject had to send a message to an experimenter or web browsing with their own smartphone (mean weight: 152.2 ± 10.3 g) in seated position on a chair with a height of 0.46 m (H_{Seat}, Figure 1).

Two situations were investigated: sitting without support (SWT) and sitting with a support (ST) materialized by a table (table height of 0.76m, $H_{Support}$, Figure 1A).

An optoelectronic system with 8 infrared cameras (Oqus 400, Qualisys AB, Gothenburg, Sweden) at a frequency of 200 Hz was used to capture the kinematics. Thirty six reflexive markers were attached to trunk, head, and upper limb body anatomical landmarks in agreement with the ISB recommendations (25). Moreover, five additional markers were added on the smartphone to know its position and orientation in relation to the user (Figure 2). To not disturb the subject during the experiment, a light weight resin support glued to the back of the smartphone was used to support the five markers. Following the ISB instructions, a local coordinate system was defined for each considered segment (head, trunk, arms, forearms, and hands) from de 3D markers positions. Then, the relative the upper body joint angles (neck, trunk, shoulders, elbows, and wrists) were computed at each step of the movement to characterize the subject posture.

The comparison with the model was conducted in the sagittal plane. All conditions were reproduced 3 times and the subjects were to behave as naturally as they would in their daily life. Furthermore, the reaction force of the chair on the backside and of the support were also recorded during the experiment with a force plate (Type 9260AA, Kistler Instrumente AG, Winterthur, Switzerland) and compared to reaction forces computed by the model for each subject and each situation (SWT and ST).

All experimental data were recorded less than 1 minute long and have been averaged on the full trial. These measurements were compared to the values estimated by the predictive model using the weight and height of each subject in the same environmental conditions as in the experiments. Table 1 summaries the mean absolute errors respectively for the SWT and ST conditions for two strategies in texting task and three strategies in web browsing condition extracted from Merbah et al. (20). They have been selected to cover the largest joint angles range of motion.

Figure 2: Experimental setup representing one subject fully equipped during texting in SWT condition (left) and during web browsing in ST condition (right).

For without support condition (SWT), the error varied between 1.4 and 15.4 ° with an average of 6.0 ± 4.2 °. The highest values were obtained at the elbow independently of the task and the strategy with an average of 13.2 ± 2.3 °, varying between 10.8 ° and 15.4 °. Regardless of the condition or strategy, the model overestimates elbow flexion. For the other joints, the values computed by the model are equal to the experimental values depending on the subjects, conditions and strategies. It is noted that for the neck and the trunk, an average error of 2.9 ± 1.3° was obtained, with an error of 2.8 ± 0.9° and of 3.0 ± 1.7° respectively for the neck and the trunk.

In the condition with support (ST), global error less than 11° (1.5° à 11.1°). However, for the WB Trunk strategy 1, the shoulder presented a large mean error 26.7 ± 7.4°. As with ST condition, the predictive model overestimates elbow flexion relative to the experimental data.

The results showed differences of about 50 N for the estimation of pelvis reaction force in SWT condition while the difference is twice as large (about 130N) in the SWT condition independently of the strategies and tasks. In both cases the forces are underestimated by the model. In contrast, the model overestimated the elbow reaction force of about 100N.

Figure 3 presents a visual comparison of results obtained by the model and recorded postures projected in sagittal plan. In order to ensure the model performance, different morphologies were chosen with BMIs of 16.8, 20.8, 31.0. The model is faithful to the postures adopted by the subjects in majority of cases in the proportions presented in Tables 1. The greatest differences were observed at the distal part of the upper limb, mainly related to the smartphone position where the flexion of the shoulder and elbow seems to be the cause.

Table 1: Mean and standard deviation of average absolute error for the two tasks seated and the two experimental conditions (SWT and ST)

SWT condition	Texting task									Web browsing task											
	G2 strategy (Neck)				G4 strategy (Neck-Trunk)					G1 strategy (Neck)				G2 strategy (Neck-Trunk)				G4 strategy (Neck-Trunk)			
	Min	Max	Mean	*(STD)*	Min	Max	Mean	*(STD)*		Min	Max	Mean	*(STD)*	Min	Max	Mean	*(STD)*	Min	Max	Mean	*(STD)*
Trunk flexion (°)	0.9	4.5	**2.6**	*(1.2)*	0.6	4.0	**2.6**	*(1.4)*		0.2	3.8	**1.4**	*(1.2)*	0.3	5.6	**2.5**	*(1.6)*	1.6	9.0	**5.8**	*(2.4)*
Neck flexion (°)	0.2	6.9	**3.4**	*(2.1)*	1.9	6.5	**3.7**	*(1.9)*		0.2	5.8	**2.4**	*(2.0)*	0.9	6.0	**3.2**	*(1.8)*	0.6	4.1	**1.4**	*(1.3)*
Shoulder flexion (°)	0.5	8.2	**4.2**	*(2.2)*	4.9	14.7	**9.6**	*(4.7)*		0.9	10.2	**5.2**	*(2.6)*	0.3	6.4	**3.7**	*(2.1)*	3.9	11.4	**7.9**	*(2.3)*
Elbow flexion (°)	2.8	33.2	**15.3**	*(10.6)*	13.5	17.6	**15.4**	*(1.8)*		1.0	24.2	**10.9**	*(7.6)*	1.7	18.8	**10.8**	*(5.2)*	5.7	18.7	**13.6**	*(4.2)*
Wrist Ulnar deviation (°)	0.1	13.7	**5.3**	*(4.3)*	1.0	6.7	**3.4**	*(2.0)*		0.1	8.9	**3.4**	*(2.5)*	0.8	13.1	**6.5**	*(4.0)*	0.1	17.8	**7.0**	*(6.4)*
Pelvis reaction force (N)	44.5	87.6	**56.0**	*(15.9)*	38.9	45.4	**42.1**	*(4.6)*		48.2	78.2	**56.7**	*(14.4)*	44.5	87.6	**60.7**	*(18.7)*	38.9	45.4	**42.3**	*(3.3)*

ST condition	Texting task									Web browsing task											
	G1 strategy (Trunk)				G4 strategy (Neck-Trunk)					G2 strategy (Neck-Trunk)				G4 strategy (Trunk)				G1 strategy (Trunk)			
	Min	Max	Mean	*(STD)*	Min	Max	Mean	*(STD)*		Min	Max	Mean	*(STD)*	Min	Max	Mean	*(STD)*	Min	Max	Mean	*(STD)*
Trunk flexion (°)	0.2	3.5	**1.7**	*(1.0)*	0.7	7.4	**3.6**	*(2.2)*		0.5	8.5	**4.2**	*(2.7)*	0.9	6.2	**2.3**	*(1.9)*	0.1	2.9	**1.5**	*(1.0)*
Neck flexion (°)	0.9	4.7	**2.3**	*(1.2)*	0.1	8.4	**4.0**	*(2.7)*		0.2	5.6	**2.7**	*(2.1)*	1.1	7.3	**3.5**	*(2.2)*	0.6	5.8	**2.1**	*(1.5)*
Shoulder flexion (°)	2.9	14.2	**8.3**	*(4.0)*	0.1	7.3	**2.0**	*(2.0)*		0.5	3.0	**1.2**	*(0.7)*	15.9	35.4	**26.7**	*(7.4)*	4.2	15.8	**10.1**	*(4.1)*
Elbow flexion (°)	5.2	18.5	**10.7**	*(4.5)*	1.0	15.1	**6.5**	*(4.2)*		0.5	10.6	**5.1**	*(3.6)*	0.2	16.0	**7.5**	*(7.6)*	6.1	16.4	**11.1**	*(3.3)*
Wrist Ulnar deviation (°)	0.5	4.3	**2.2**	*(1.2)*	1.9	13.7	**6.0**	*(3.5)*		0.1	12.7	**5.2**	*(3.7)*	1.4	8.0	**3.3**	*(2.5)*	0.8	18.9	**9.4**	*(6.2)*
Pelvis reaction force (N)	105.2	215.2	**171.0**	*(58.1)*	101.7	130.6	**113.8**	*(14.4)*		100.3	128.4	**114.5**	*(15.5)*	52.1	58.3	**55.2**	*(4.4)*	104.8	214.9	**181.8**	*(52.4)*
Elbow reaction force (N)	91.3	190.2	**150.6**	*(52.3)*	70.9	95.0	**81.5**	*(11.6)*		71.3	93.4	**82.1**	*(12.1)*	19.0	21.8	**20.4**	*(1.9)*	91.0	189.9	**160.2**	*(47.1)*

Neck strategy, Trunk strategy and Neck-trunk strategy refer to NSTRAT, TSTRAT and MSTRAT proposed by Merbah et al. (20).

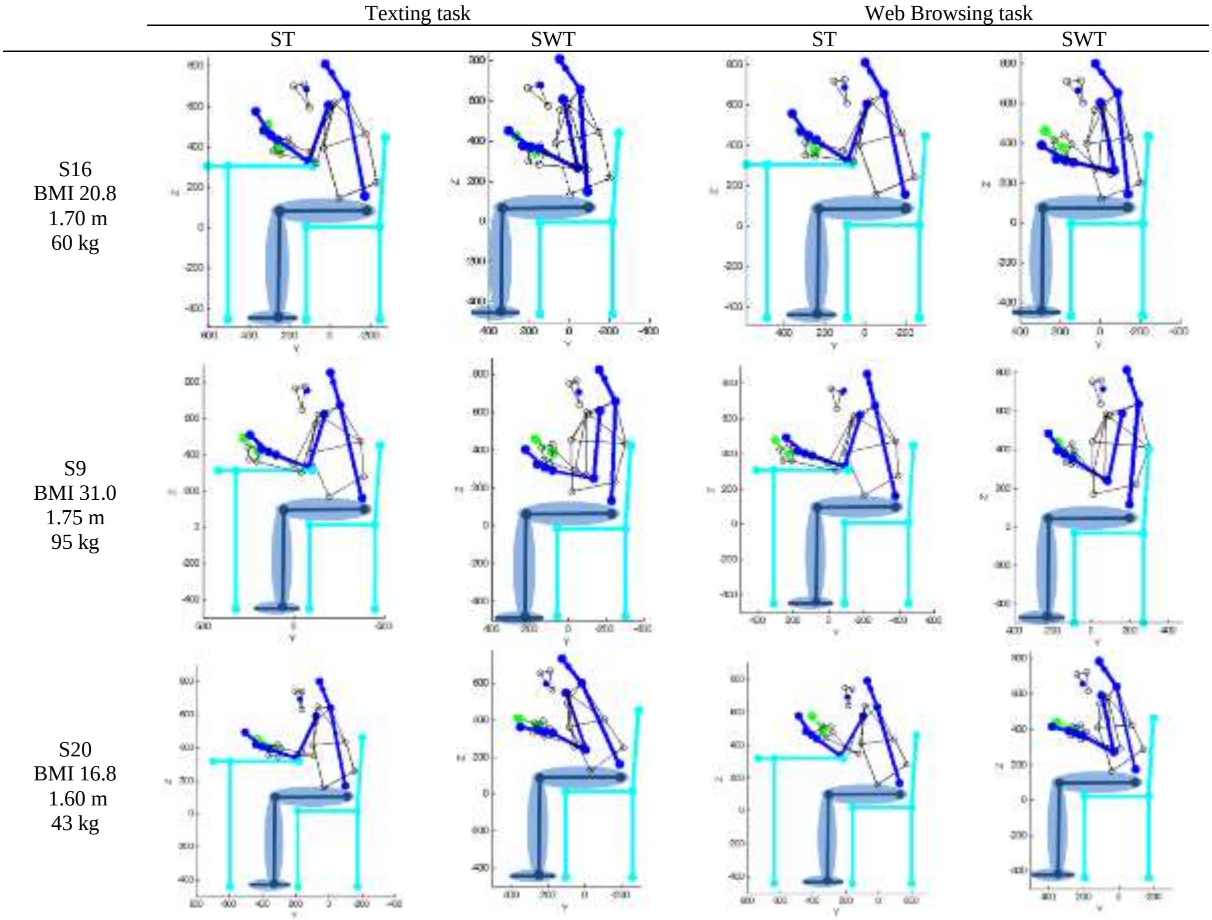

Figure 3: Data comparison between model results (thick blue line) and the experimental data (thin black line).

RESULT

Joint torques and reaction force estimation – BMI 12.5 to 50

Tables 2 and 3 presents the simulation results for one strategy selected among those reported by Merbah et al. (20): a trunk strategy for ST condition and a Neck-Trunk for the SWT condition (corresponding respectively to TSTRAT and MSTRAT according to Merbah et al. study). They have been selected because they presented de highest values of neck and trunk flexion during texting and web browsing tasks. The simulations were carried out for the fourteen BMIs (between 12.5 and 50, representing the different body types) and for the two interaction tasks (texting and web browsing task with a 0.150 kg smartphone) with an elbows/forearms (table) support height of 0.76 m and a seated height of 0.46 m. As expected, selected strategy affected all the models parameters in relation to the neck and truck flexions. Indeed, the posture with the highest trunk flexion (29.6° in the ST condition) presented the highest joint torques values, up to 130N. It is also observed that the greater the trunk flexions, the more reaction forces in ST condition tend to be equally distributed between pelvis and elbows. When the trunk flexion was lower (Table 3), shoulder flexion was observed which is very much reduced with an increase of the elbow flexion.

Table 2: Simulation results for a texting and a web browsing tasks in ST condition with a support height of 0.76 m, a seat height of 0.46 m, and for the 14 selected BMIs when considering the Trunk strategy data (corresponding to TSTRAT form Merbah et al., (20)). Because the two tasks were considered symmetrical, the values obtained for the upper limb joints (shoulder, elbow and wrist) apply for both sides.

			Reaction forces (N)			**Joint angles (°)**						**Joint Torques (N.m)**				
	Task	**BMI**	**F1**	**F2**		**Neck flex**	**Trunk flex**	**Shoulder flex**	**Elbow flex**	**Wrist flex**		**Neck**	**Trunk**	**Shoulder**	**Elbow**	**Wrist**
With support ST condition	Texting	12,5	186,3	180,3		6,7	29,6	59,6	105,0	0,0		1,9	53,5	1,0	1,4	0,2
		13,1	154,6	139,0		6,7	29,6	68,6	95,0	0,0		1,4	39,3	0,9	1,1	0,2
		18,3	173,8	149,0		6,7	29,6	76,6	87,0	0,0		1,3	40,1	1,0	1,0	0,2
		18,8	279,9	269,2		6,7	29,6	59,6	105,0	0,0		2,9	80,3	1,5	2,0	0,3
		25,0	373,5	358,2		6,7	29,6	59,6	105,0	0,0		3,9	107,1	2,0	2,5	0,3
		25,4	256,0	220,1		6,7	29,6	74,6	89,0	0,0		2,0	60,4	1,5	1,4	0,2
		29,8	444,7	425,8		6,7	29,6	59,6	105,0	0,0		4,6	127,4	2,4	2,9	0,3
		30,0	284,8	242,4		6,7	29,6	76,6	87,0	0,0		2,2	65,6	1,6	1,5	0,2
		34,5	328,5	279,1		6,7	29,6	76,6	87,0	0,0		2,5	75,6	1,9	1,7	0,2
		34,6	476,5	437,8		6,7	29,6	63,6	101,0	0,0		4,6	129,4	2,7	2,9	0,3
		39,5	493,0	443,2		6,7	29,6	66,6	97,0	0,0		4,5	128,0	2,8	2,9	0,3
		39,5	376,1	319,1		6,7	29,6	76,6	87,0	0,0		2,9	86,6	2,2	1,9	0,2
		47,8	510,4	440,4		6,7	29,6	72,6	91,0	0,0		4,2	123,1	3,0	2,7	0,3
		49,9	475,3	402,5		6,7	29,6	76,6	87,0	0,0		3,6	109,4	2,7	2,3	0,3
	Web browsing	12,5	177,1	189,5		7,5	25,7	48,7	109,0	0,0		1,8	49,3	0,8	1,5	0,2
		13,1	151,5	142,0		7,5	25,7	59,7	98,0	0,0		1,3	36,3	0,8	1,1	0,2
		18,3	172,4	150,4		7,5	25,7	68,7	89,0	0,0		1,2	37,2	0,9	1,1	0,2
		18,8	266,1	283,1		7,5	25,7	48,7	109,0	0,0		2,7	74,0	1,2	2,1	0,3
		25,0	355,2	376,6		7,5	25,7	48,7	109,0	0,0		3,6	98,6	1,6	2,7	0,3
		25,4	252,4	223,7		7,5	25,7	65,7	92,0	0,0		1,9	56,0	1,4	1,5	0,2
		29,8	422,8	447,6		7,5	25,7	48,7	109,0	0,0		4,3	117,3	1,9	3,1	0,4
		30,0	282,7	244,6		7,5	25,7	68,7	89,0	0,0		2,0	60,9	1,5	1,6	0,2
		34,5	326,0	281,6		7,5	25,7	68,7	89,0	0,0		2,3	70,2	1,8	1,8	0,2
		34,6	461,0	453,3		7,5	25,7	53,7	105,0	0,0		4,3	119,4	2,3	3,0	0,4
		39,5	482,4	453,8		7,5	25,7	57,7	100,0	0,0		4,2	118,2	2,5	3,0	0,3
		39,5	373,2	322,0		7,5	25,7	68,7	89,0	0,0		2,7	80,3	2,0	2,0	0,3
		47,8	502,5	448,3		7,5	25,7	63,7	94,0	0,0		3,9	114,0	2,7	2,8	0,3
		49,9	471,7	406,1		7,5	25,7	68,7	89,0	0,0		3,4	101,5	2,6	2,4	0,3

Table 3: Simulation results for a texting and a web browsing tasks in SWT condition with a seat height of 0.46 m and for the 14 selected BMIs when considering the Neck-Trunk strategy data (corresponding to MSTRAT form Merbah et al., (20)). Because the two tasks were considered symmetrical, the values obtained for the upper limb joints (shoulder, elbow and wrist) apply for both sides.

			Reaction forces (N)		**Joint angles (°)**					**Joint Torques (N.m)**				
	Task	**BMI**	**F1**	**F2**	**Neck flex**	**Trunk flex**	**Shoulder flex**	**Elbow flex**	**Wrist flex**	**Neck**	**Trunk**	**Shoulder**	**Elbow**	**Wrist**
Without support SWT condition	Texting	12,5	366,6	-	14,1	25,0	11,0	131,1	18,2	2,1	48,8	0,3	2,1	0,3
		13,1	293,6	-	14,1	25,0	9,0	118,3	3,4	1,5	36,0	0,2	1,7	0,3
		18,3	322,8	-	14,1	25,0	10,0	104,6	9,3	1,4	36,9	0,3	1,6	0,2
		18,8	549,2	-	14,1	25,0	11,0	131,1	18,2	3,1	73,2	0,2	2,9	0,4
		25,0	731,7	-	14,1	25,0	11,0	131,1	18,2	4,2	97,7	0,2	3,6	0,5
		25,4	476,1	-	14,1	25,0	10,0	108,2	5,7	2,2	55,5	0,3	2,3	0,3
		29,8	870,5	-	14,1	25,0	11,0	131,1	18,2	4,9	116,2	0,1	4,2	0,5
		30,0	527,3	-	14,1	25,0	10,0	104,6	9,3	2,3	60,4	0,3	2,4	0,3
		34,5	607,6	-	14,1	25,0	10,0	104,6	9,3	2,7	69,6	0,3	2,7	0,3
		34,6	914,3	-	14,1	25,0	10,0	126,4	12,5	4,9	118,2	0,0	4,4	0,5
		39,5	936,2	-	14,1	25,0	10,0	121,0	7,1	4,8	117,1	0,1	4,3	0,5
		39,5	695,2	-	14,1	25,0	10,0	104,6	9,3	3,1	79,6	0,3	3,0	0,4
		47,8	950,8	-	14,1	25,0	10,0	111,7	2,2	4,5	113,0	0,2	4,2	0,5
		49,9	877,8	-	14,1	25,0	10,0	104,6	9,3	3,9	100,6	0,3	3,7	0,4
	Web browsing	12,5	366,6	-	21,5	12,8	4,8	126,9	15,2	1,9	35,0	1,0	2,0	0,3
		13,1	293,6	-	21,5	12,8	4,8	113,4	1,7	1,3	26,3	0,9	1,6	0,2
		18,3	322,8	-	21,5	12,8	5,8	98,9	11,8	1,3	27,4	1,0	1,6	0,2
		18,8	549,2	-	21,5	12,8	4,8	126,9	15,2	2,8	52,5	1,3	2,8	0,4
		25,0	731,7	-	21,5	12,8	4,8	126,9	15,2	3,7	70,0	1,6	3,6	0,4
		25,4	476,1	-	21,5	12,8	5,8	102,7	8,0	1,9	41,1	1,3	2,2	0,3
		29,8	870,5	-	21,5	12,8	4,8	126,9	15,2	4,4	83,3	1,8	4,2	0,5
		30,0	527,3	-	21,5	12,8	5,8	98,9	11,8	2,1	44,9	1,4	2,4	0,3
		34,5	607,6	-	21,5	12,8	5,8	98,9	11,8	2,4	51,8	1,6	2,7	0,3
		34,6	914,3	-	21,5	12,8	4,8	122,0	10,3	4,4	85,4	1,9	4,3	0,5
		39,5	936,2	-	21,5	12,8	4,8	116,4	4,7	4,3	85,2	2,0	4,3	0,5
		39,5	695,2	-	21,5	12,8	5,8	98,9	11,8	2,7	59,3	1,7	3,0	0,4
		47,8	950,8	-	21,5	12,8	4,8	106,8	4,9	4,0	83,3	2,1	4,2	0,5
		49,9	877,8	-	21,5	12,8	5,8	98,9	11,8	3,5	74,9	2,1	3,7	0,4

Risk Scales

Table 4 presents the simulation results carried out for seat heights varying between 0.45 and 0.5 m, support heights from 0.75 to 0.8 m and for manipulated masses varying from 0.01 to 1 kg depending on the BMI to cover a wide variety of combinations present in daily life. Figure 4 illustrates through an abacus the joint values of the upper body to which the RULA code has been associated in the background. This synthetic representation provides an easy and quick risk assessment. Joint torques and support forces were computed based on environmental parameters and subject anthropometry (BMI). This information is shown in Figure 4. A risk scale has been proposed for upper body joint torques based on data from the literature.

A first phase consists in using the maximum joint torques measured. Studies have reported maximum extensor torques of 6.62 Nm.Kg-1 for the cervical spine (29) and 4.6 Nm.Kg-1 for the lumbar spine (30). For a man with an average weight of 80 kg, it corresponds respectively to maximal joint torques of 530 Nm and 368 Nm. For the upper limb, Koski and McGill (31) reported a maximal shoulder flexion torque of 89.9 Nm and Guenzkofer et al. (32) found a maximal elbow flexion torque of 60 Nm. Vieira et al. (33) measured a maximum radial deviation torque of 5 Nm. From a physiological consideration, a force can be maintained for a long time or moved over many repetitions when it is less than 50% of the MVC (34). Therefore, it can be assumed that this muscular constraint does not present any particular risk of MSDs. The threshold was reduced to 20% in this work because static postures seem to generate higher fatigue levels and higher discomfort scores than dynamic postures (22). All of this information helps define the zone in which the risk of developing MSDs is very low. The corresponding score was set to 1. This area is presented in green in the Figure 5 for the four considered joints. A second phase uses comfort scales to define risk zones. According to the work of Nah et al. (35) and Kee and Lee (36), there is a link between external load and perceived discomfort, characterized by a score, at the shoulder and neck. Using a Borg CR10, they report a discomfort score of 6 scale for a 90° shoulder flexion and a 45° elbow flexion when a 3 kg load was handled, corresponding to a perceived discomfort more than strong. It has been shown that discomfort is strongly linked to the onset of MSDs (37). It can be assumed that the risk of MSDs is greater beyond this value. Applied to an individual with an average height of 1.80m, two additional thresholds of 49 Nm and 17 Nm were obtained for the shoulder and elbow. These values correspond to the limit between the medium (rated at 2, represented in yellow, Figure 5) and high risk zone (rated at 3, represented in red color, Figure 5) of developing MSDs.

Table 4: Range of estimated values by the model for a texting task and a web browsing tasks in seated position with a seat height between 0.45 and 0.5m, a support height between 0.75m and 0.8m, for a handled load between 10g and 1kg when considering all strategies defined in the Merbah et al. (20) work, i.e. NSTRAT, TSTRAT and MSTRAT.

	ST		**SWT**	
	Min	**Max**	**Min**	**Max**
F1 – seat reaction force (N)	54.2	538.4	293.6	950.8
F2 – support reaction force(N)	127.6	746.3	-	-
Neck flexion (°)	2.0	19.7	14.1	25.2
Trunk flexion (°)	11.6	29.6	1.1	25.0
Dominant Shoulder flexion (°)	12.6	89.6	1.1	11.0
Dominant Elbow flexion (°)	53.0	115.0	104.3	134.5
Dominant Wrist flexion (°)	0	0	1.3	25.8
Neck torque (N.m)	0.6	4.6	1.0	5.0
Trunk torque (N.m)	25.2	129.4	16.4	118.3
Dominant Shoulder torque (N.m)	0	3.6	0	4.2
Dominant Elbow torque (N.m)	0.6	6.8	1.5	4.4
Dominant Wrist torque (N.m)	0.1	1.4	0.2	0.5

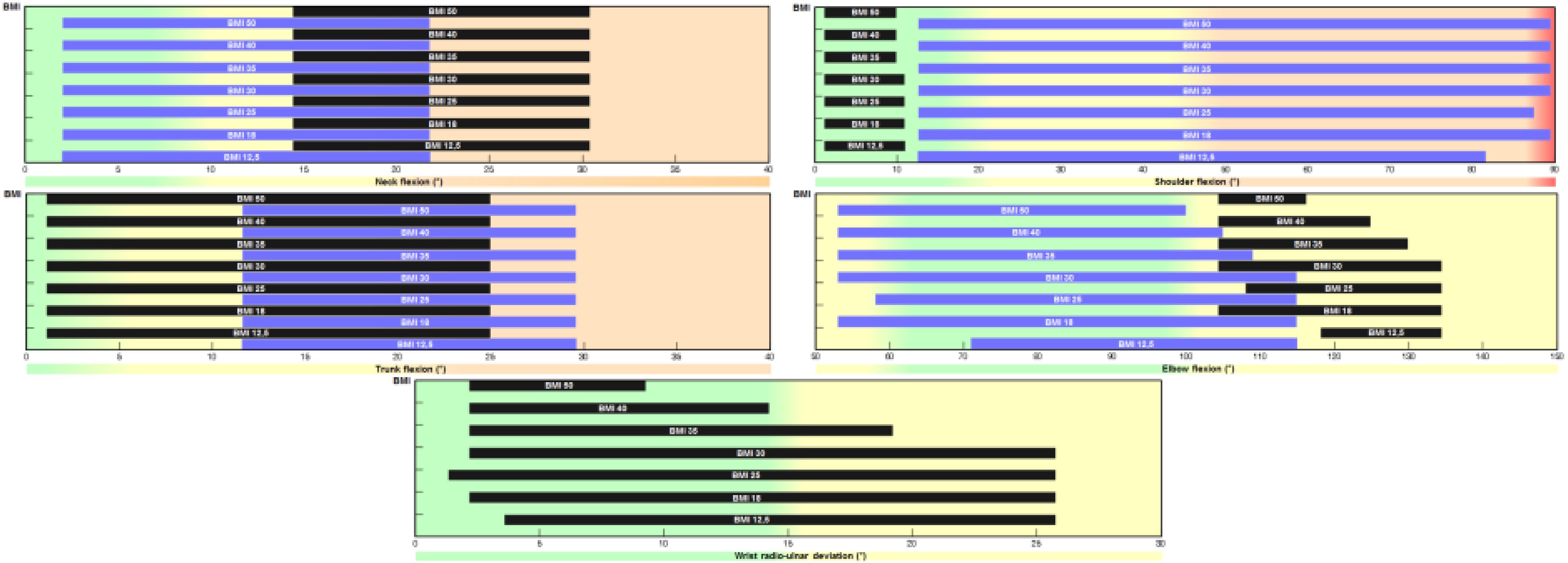

Figure 4: Joint angles estimated by the model depending on the body mass index for an upper limb support height varying from 0.75 to 0.8 m, a seat height varying from 0.45 and 0.5 m and for manipulated loads ranging from 0.01 to 1kg when considering all texting and web browsing strategies (Merbah et al. (20)). For the neck, trunk, shoulder and elbow flexion, the color scale in the background represents the posture score directly from the RULA (8): the green part corresponds to a score of 1, the yellow part to a score of 2, the orange part to a score of 3, and the red part to a score of 4.

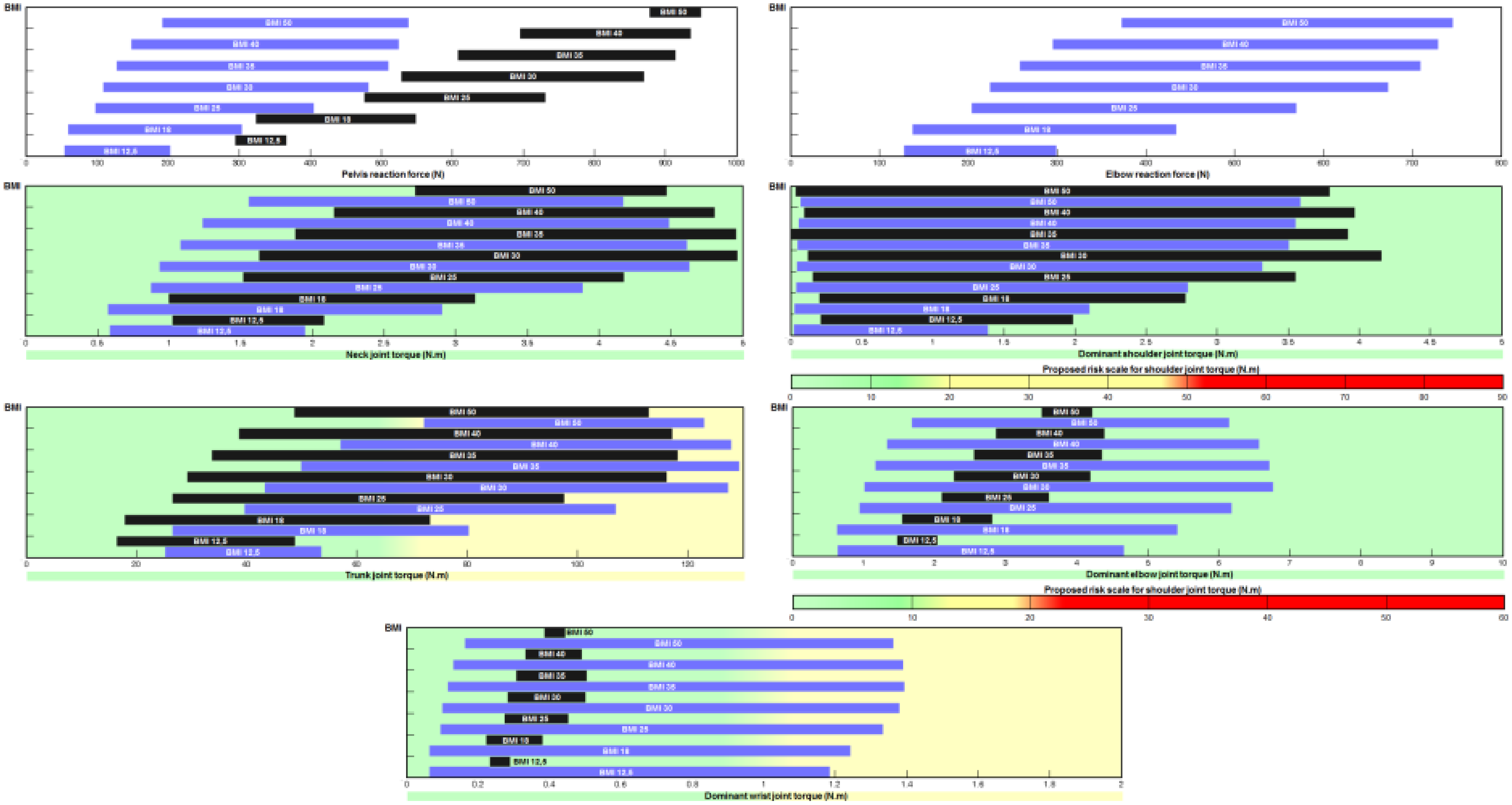

Figure 5: Reaction forces and joint torques estimated by the model depending on the body mass index for an upper limb support height varying from 0.75 to 0.8 m, a seat height varying from 0.45 and 0.5 m and for manipulated loads ranging from 0.01 to 1kg when considering all texting and web browsing strategies (Merbah et al. (20)). The color scales correspond to the risk scales constructed from the joint torque values.

DISCUSSION

The aim of this work was to propose a predictive model and value charts coupled with risk scales. This original predictive model is simple to use and requires as input: subject anthropometric characteristics, environmental constraints as and the head/trunk postural strategy. By coupling this data with the information contained in the anthropometric tables (28), the model is able to give an estimate of 11 (when seated without any support) or 12 (seated with an upper limb support) parameters divided into 3 groups.

First, the predictive model estimates the upper limb joint angles (shoulder, elbow, and wrist) in the sagittal plane. This quantification is necessary to carry out ergonomic assessments of the task and to be able to characterize the risks of MSD occurrence, as presented in several ergonomic tools in the literature (8, 9). Although the thresholds may vary from one tool to another, all the approaches agree that the most constraining postures (i.e. far from the joint neutral) are associated with significant discomfort and high risks of developing MSDs. Comparison with experimental measurements (Table 1) showed that the model errors were very low for neck and trunk in the seated position. Whether the support is present or not, average deviations were less than 3°. This result is directly related to of the model’s consideration of several postural strategies to perform a texting or web browsing task with a smartphone, as reported by Merbah et al. (20) in a previous work. Indeed, adding this information as an input variable allowed the model to further represent the different postures likely to be encountered in real life. Shoulder flexions showed very satisfactory results in the unsupported condition. In contrast, for the Trunk strategies in the supported condition the differences with the experimental values were more important (10° or more). It would seem that in situations with significant trunk flexion, shoulder flexion estimation is greatly altered by movements performed in the other planes, particularly abduction in frontal plane. This phenomenon was compensated but not in totality by the application of weighting parameters for segmental lengths. A similar observation can be made for elbow flexion, which seems to be the joint in the model that was the most sensitive to strategies, with average variations of between 5 and 15°. Indeed, smartphone grasping requires a medial shoulder rotation in the horizontal plane, which considerably affects elbow flexion estimation in the sagittal plane. In addition, face-to-smartphone distance and handling of the phone may also directly affect its computation, which could explain the differences with the experimental data (Figure 3). One limitation was that the model does not consider the different support possibilities in the ST condition. Indeed, the model considers that the subject is leaning on the elbows during smartphone interactions. However, it would be possible that some users can be supported on the whole forearms or be supported on the edge of the table with part of the forearms more or less far from the elbow. It would be interesting to take this aspect into consideration to refine the of shoulder and elbow joint angles computation.

Secondly, the model provides information about joint torques and reaction forces at the seat and support when it is present. This information is important to characterize MSDs risks and is included in evaluation grids of tools such as RULA, for example. However, it only appears as an additional criterion in the form of the external mass handled. The contribution of this work was to objectively quantify these parameters so that they could be used to propose an MSD risk scale. The proposed approach uses the subject's anthropometric data directly to provide a personalized assessment. The comparison with the experimental data showed that the model was fairly faithful to reality with regard to the reaction forces at the pelvic. These forces were recurrent underestimation of about 50N whatever the strategy for the unsupported condition. This difference could be explained by the fact that the model does not include the lower limbs and a part of their mass exerts a force on the seat. In contrast, the differences were more important in the supported condition. The model underestimated the pelvic reaction force by about 130N and overestimated the elbow reaction force by about 100N. It appears that when the trunk flexion was significant, the model would transfer a significant portion of the pelvic reaction forces from the seat to the elbows. Since the model does not take into account the lower limbs, the reaction force was applied at the root of the model, i.e. the sacrum (point A, Figure 1). This consideration would result in a greater distance from the center of gravity and therefore less pelvic reaction forces than in reality. Considering at least the thigh segment could allow adjusting the application point of this force and reducing the discrepancies observed with the experimental data.

The mode also provides an estimation of upper body joint torques. Several works have shown their importance because they are the image of the muscular solicitation necessary to maintain a posture (21). It is recognized in the literature that high muscle loading causes discomfort in subjects and therefore represents a risk factor for the development of MSDs (38, 39). As presented, the model allows the computation of joint torque values by taking into account environmental conditions (seat and support heights), subject's anthropometric data and neck/trunk strategies. By generalizing these input data, Figure 5 and Table 4 presented upper body joint torques and reaction forces amplitudes as a function of the subject's BMI for a wide range of environmental configurations with or without support, whatever the strategy used.

The MSDs risk assessment is an important issue for the health of individuals, particularly in the industrial environment. Knowing these risks upstream is a relevant aspect in ergonomics for developing adapted workstations with low risk exposure to MSDs, as shown in previous work with the use of the NERPA (11). The graphical tool presented in figures 4 and 5 presents all parameters amplitudes estimated by the model that are likely to be encountered in daily life. These ranges took into account different environmental configurations and possible postural strategies. These charts allow a quick risk estimation incurred by an individual in a given situation. The addition to risk scales based on the RULA recommendations for posture, the proposed scales for joint torques provides a direct characterization of the different levels of risk associated with the sitting situation. These proposed scales provide indicators that will help to provide recommendations for MSD prevention. As described during their construction, the joint torques risk scales limits were based on numerous studies but require further investigation to be refined, particularly for the neck and the trunk.

CONCLUSION

In this paper, the structure and validation process of a sagittal upper body model based on anthropometric data of individuals for texting and a web browsing task, were presented. The consideration of multiples neck/trunk strategies improved its robustness. The model provided a quantification of posture as well as joint torques and reaction forces from few input data. The generalization of the model including variations in seat height and support allowed to estimate the range of each model parameter as a function of the subject body mass index. A graphic tool was proposed to quickly identify (from postural and joint torques risk scales) the risk of developing MSDs in seated position.

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