Virtual reality environment for fatigue disassembly task evaluation

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Résumé— This paper aims to better understand how Virtual reality (VR) is influencing on human behavior with using biomechanical analysis methods and its application for assembly/disassembly operations simulation in particular. For this purpose, a new haptic model for mechanical energy expenditure is proposed where the required mechanical work is used as main parameter. Then, the fatigue levels are evaluated by analyzing the recorded electromyography (EMG) signal on the four involved muscles of operator's arm. The proposed method is validated by a set of experimental disassembly tests performed in a VR environment. The comparison of the analytical and experimental results has shown good correlation between them. The proposed method provides the feasibility to integrate human muscle fatigue into disassembly sequence evaluation via mechanical energy expenditure when performing disassembly operation simulations in the initial stage of product design.

Mots-clés— virtual reality environment, dssembly sequences evaluation, muscle metabolic energy, mechanical energy, muscle fatigue

I. INTRODUCTION

Simulations closely related with Assembly/Disassembly (A/D) operations represent important research subject today. These A/D operations are often considered in the initial stage of product design. In order to evaluate disassembly sequences different tools and Virtual Reality (VR) human-computer interfaces are proposed [1, 2]. As the VR set-up can be easily modified, designer can quickly adjust the design of product [3]. Preliminary evaluation of disassembly sequences during product design is a very important issue. Thus, for disassembly task of complex products, two questions are arising, namely*: i).* disassembly sequence generation*; ii).* disassembly sequence evaluation. This paper is focusing on the second one.

In this context, it considers the operator's hand muscle fatigue factors in evaluation of fatigue associated with disassembly task. Thus, a new method for evaluating the hand fatigue associated with disassembly task by utilizing metabolic energy expenditure is proposed. Before displacement, the components/modules linked by fasteners (screws, clips) must be separated. Thus we assume that the two main parameters for carrying out the calculation of metabolic energy expenditure for disassembly tasks are: i). the *weights* of the components; ii). the *disassembly paths* of the components.

For this purpose, disassembly experiments in VR were performed in order to evaluate fatigue with electromyography (EMG) analysis. Our method shows that using EMG data can give relevant information about the subject muscle state, which could be of interest in the field of evaluation of disassembly task. During the task (subjects in standing position), the EMG signals on the four most involved muscles of operator's arm namely: *extensor carpi radialis* (*ECR*), *flexor carpi radialis* (*FCR*), *biceps* and *triceps* are recorded. This capture of muscular contractions is the reason to limit the observed movements in quasi-static motion. Consequently in the proposed method only the calculation of the energy expended by the hand with only vertical displacements are taken into account. The energy expenditure for the operator to maintain his/her standing position during the test is a source of fatigue which is not included in the proposed method.

The results of this study may be useful for product designers as a decision-making tool allowing them to evaluate the muscle fatigue level while performing disassembly sequences.

II. Previous work

The literature analysis carried out within this study shown that certain existing approaches for disassembly evaluation, some integrated in VR, were proposed by taking into account different criteria such as: *i).* visibility score [4]; *ii).* set of directions for removal (SDR) [5] ; *iii).* stability of sub-assembly [5, 6], iv). disassembly time [7]; *v).* combination of multiple ergonomic factors [5, 6, 7]; *vi).* disassembly cost [8]; *vii).* number of necessary tools for disassembly [6, 9]. However, they do not take into account the muscle fatigue of the operator for different conditions of requests (postures, loads, …), which in our opinion is highly influencing work's efficiency and very important today with the increasing of the retire age of the operators.

Trying to avoid uncertainty of disassembly operation process, Tian et al. [10] proposed a method to calculate the probability of disassembly energy's distribution and the minimal energy expenditure in a disassembly sequence. The minimal energy for each disassembly sequence is estimated. However, the authors pointed out that the probable energy expenditure intervals of several disassembly sequences had the possibility to overlap with each other.

Predicting metabolic energy consumption associated with a disassembly sequence can be a criterion for evaluating the fatigue level induced by a disassembly sequence. In this optic Bisi [11] proposed an EMG (Electromyography) *driven model* for predicting metabolic energy consumption during physical effort. It includes EMG signals from active muscles associated with some kinematic joint parameters. However, it is too complex to be applied in the disassembly operation evaluation, because it is quite time consuming to perform energy disassembly sequence and predict its metabolic energy consumption which requires a motion capture analysis system coupled with EMG data processing.

A long time repeatedly performed training may activate the neural adaption of muscles by changing their activation mode. Rube and Secher [12] performed leg task. The results of comparison between the maximum voluntary contractions (MVCs) values before and after training shown that one-legged group of subjects was less tired when performing one-legged task, and two-legged group was less tired during two-legged task. It was mentioned in [13, 14] that the effect of training on fatigue depends on training mode. For a disassembly sequence, for instance, loading level, loading time and operation posture are not always the same.

Considering the ergonomic factor during the disassembly task, many works focus on: i). calculating the energy expenditure [9]; ii). predicting the muscle fatigue associated with the specific task [15]; iii). predicting the energy assumption associate with the specific task [11] ; iv). modeling the work-recovery ratios [16].

The fatigue of muscles being an important factor affecting the efficiency of performing disassembly task, its evaluation is the aim of our work. One possibility for this evaluation is to calculate the slope of median frequency of EMG signals [16]. More the slope of median frequency decreases, more muscle fatigue there is [18]. It was proven that the peak value of EMG signals after root mean square (RMS) processing is also an index of fatigue [19]. Thus, a new method of predicting the fatigue during disassembly task in VR environment is proposed here.

III. Method for fatigue level evaluation

A. Hypothesis and basic principles

We assume that [20]:

Hypothesis 1: More mechanical energy is required to complete the disassembly task, more metabolic energy will be consumed in the human arm.

Hypothesis 2: The arm muscles, involved in the disassembly task, perform in an environment with constant temperature. The task is performed in continuous way. The fatigue accumulated in the muscle is a monotonically increasing function of the metabolic energy expenditure.

Hypothesis 3: During the disassembly task, the operator is moving the virtual objects with a given velocity in all allowed disassembly directions.

Hypothesis 4: Under the conditions of Hypotheses 1, 2 and 3, if the consumed metabolic energy for performing disassembly task 1 is bigger than this for disassembly task 2, then disassembly task 1 induces more fatigue than 2.

We present the fatigue as $FA = f\left(FA_c, FA_p\right)$, where FA_c and FA_p are respectively the fatigue in *central* nervous system and *peripheral* system (muscle). Note, that central nervous system fatigue is not taken into account in the proposed method. The metabolic energy expenditure *E* being considered as a function of *F*, *t* and *v*, then the FA_p can be expressed as:

$$\text{eq. (1) ;} \quad FA_p = f[E(F,t,v)]$$

where: $F \in (0, F_{max}]$ is the loading level; $t \in (0, t_{max}]$ is the loading time; $v = (0, v_{max}]$ is the velocity of the end of the hand.

Based on the muscle mechanical model [20], maximal muscle fatigue may be reached for different values of *F*, *t* and *v*. Thus, the boundary conditions in the proposed model are respectively: if *F* is near *0*, *t* and *v* can respectively arrive at t_{max} and v_{max} ; if F is equal to F_{max} , *t* and *v* tend to *0* (zero).

The FA_p derivative of *F* is: $\frac{dFA_p}{dF} = \frac{\partial FA_p}{\partial E} \cdot \frac{\partial E}{\partial F}$. Thus, FA_p is a monotonically increasing function of *F*, *which* means that $\frac{dFA_p}{dF} > 0$. It is obvious that $\frac{\partial E}{\partial F} > 0$ and consequently $\frac{\partial FA_p}{\partial E} > 0$ is correct in the range of loading level tested in [13] which are in agreement with those observed in our disassembly task. It means that FA_p is a monotonically increasing function of *E*.

B. Mechanical work for performing disassembly task

For disassembling the ith component, the work is:

$$\text{eq. (2) ;} \quad \Delta E_{iu} + |\Delta E_{id}| = m_i g(h_{iu} + h_{id})$$

where: ΔE_{iu} and ΔE_{id} are respectively the variation of mechanical energy when the component moves upward and downward; h_{iu} and h_{id} are respectively the vertical displacement of the mass center of the ith disassembled component along the positive (up) and negative (down) directions; m_i is the mass of the component.

Assume that there are n components to be disassembled in sequence S (task). Thus, the mechanical energy expenditure for moving the operator's arm is:

$$\text{eq. (3) : } \Delta E_{S1} = \sum_{i=1}^{n} [m_i g(h_{iu} + h_{id}) + 2m_a g h_{aiu}]$$

where: m_a is the mass of the arm; h_{ai} is the vertical displacement of the mass center of the arm between the starting point of the ith component and the position of the next component; h_{aiu} is the vertical displacement of the arm's mass center along the positive (up) direction of ith component.

The vertical displacement of the center of the arm's mass h_{aiu} is also a parameter, which has to be calculated. The arm can be geometrically abstracted as a two DOF (degrees of freedom) mechanism with three segments as shown in Fig. 1. Note that the first segment is the operator's body, supposed to be the frame of the mechanism. Gravity is defined as –**Z**.

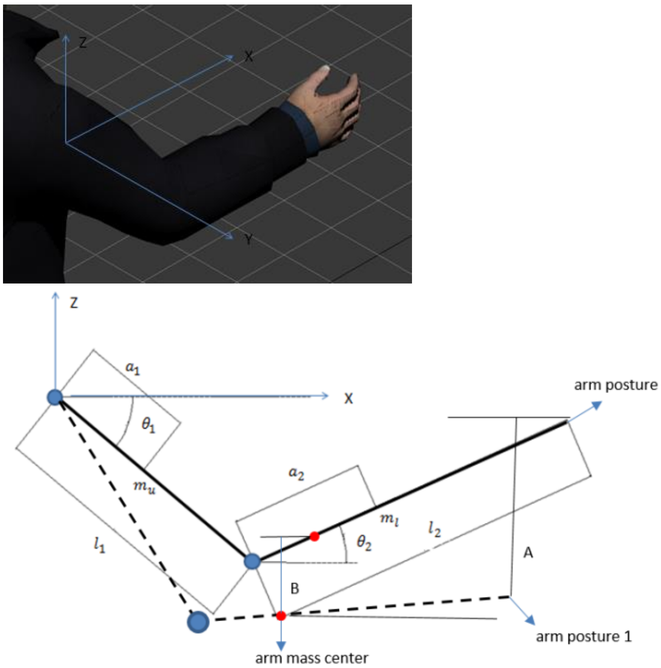

Figure 1. Arm and its associated two joint mechanism

Assume that the shoulder only rotates around $\boldsymbol{Y}$ axis. Consequently, the forearm and upper arm form the plan of ZOX. It is also assumed that the center of mass of each segment is stable inside each segment. For a given disassembly path of the ith component, the vertical displacement of the hand end point A_i between two dates t_0 and t_1 is:

$$\text{eq. (4) : } A_i = l_1 \Delta_{1i} + l_2 \Delta_{2i}$$

where: l_1 and l_2 are respectively the length of upper and lower arms; $\Delta_{1i} = sin\theta_{1i}^{t_1} - sin\theta_{1i}^{t_0}$ and $\Delta_{2i} = sin\theta_{2i}^{t_1} - sin\theta_{2i}^{t_0}$; θ_1 and θ_2 the absolute rotation angles of each segment (upper and lower arms) related to the horizontal frame axe **X.**

The vertical displacement of the arm's mass center B_i is:

$$\text{eq. (5) : } B_i = \frac{(m_u a_1 + m_l l_1)\Delta_{1i} + m_l a_2 \Delta_{2i}}{m_u + m_l}$$

where: a_1 and a_2 the relative position of mass center of upper and lower arms; m_u and m_l respectively the mass of the upper and lower arm. Then, B_i can be expressed as function of A_i and Δ_{1i} (Δ_{2i} being eliminated):

$$\text{eq. (6) } B_i = \frac{m_u a_1 l_2 + m_l l_1 (l_2 - a_2)}{(m_u + m_l) l_2} \Delta_{1i} + \frac{m_l a_2}{(m_u + m_l) l_2} A_i$$

The relation between A_i and B_i implies that the rotation angle of upper arm θ_{1i} in ZOX plan at the starting and ending point of the trajectory of the ith component has to be measured. Equation (6) gives h_{aiu} which is the module of B:

$$\text{eq. (7) : } h_{aiu} = \left| \frac{m_u a_1 l_2 + m_l l_1 (l_2 - a_2)}{(m_u + m_l) l_2} \Delta_{1i} + \frac{m_l a_2}{(m_u + m_l) l_2} A_i \right|$$

Finally, *Ai* is calculated from the disassembly path of the ith component knowing the position of start and end points.

For disassembling some components specific tools may be required. Consequently, they are considered as ordinary disassembly components moved by the operator. Note that those tools require efforts (couples, forces) which are similar with two hand disassembly operations. However, in the performed experiments one hand haptic device with force feedback was used that limits the proposed method of one point loading (weight in the mass center of the wrist).

Thus, with the proposed model, the mechanical energy expenditure for performing all the possible disassembly sequences (including moving the disassembly components, fasteners and tools) can be estimated. Note, that different disassembly sequences are potentially disassembly tasks which may induce different levels of fatigue in the muscles.

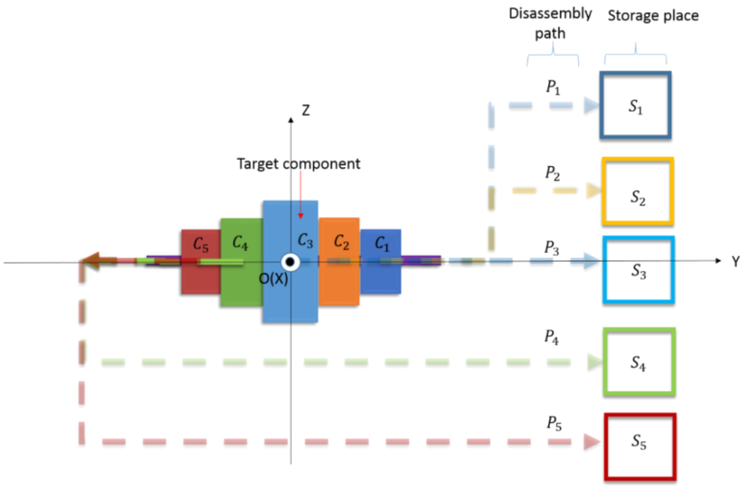

Figure 2. Mechanical assembly and parts' trajectories for disassembling target component $\boldsymbol{C_3}$

C. Example for validation

In order to illustrate the analytical model for evaluating the fatigue induced during disassembly sequence simulation, an example of a simple disassembly manufacturing process is presented here below. It consists in disassembling a five component mechanical assembly. Let the target component be component *3* as presented in Fig. 2. Each component $(C_1, C_2 \dots C_5)$ is moved from its initial position to storage place $(S_1, S_2 \dots S_5)$ following the corresponding disassembly path $(P_1, P_2 \dots P_5)$.

There are two possible disassembly sequences for disassembling the target component C_3: Sequence S1= $\{C_1, C_2, C_3\}$ and Sequence S2= $\{C_5, C_4, C_3\}$. In here, (x_{is}, y_{is}, z_{is}) and (x_{ie}, y_{ie}, z_{ie}) denote respectively the disassembly *starting* point and disassembly *ending* point coordinates of the mass center of ith component. The values of the three parameters, namely: *mass* of each component and its *starting* and *ending positions* are presented in Table1.

Mass	Value (kg)	Starting point	Value (mm)	Ending point	Value (mm)
m_1	1	(x_{1s}, y_{1s}, z_{1s})	(0,20,0)	(x_{1e}, y_{1e}, z_{1e})	(0,60,60)
m_2	1.5	(x_{2s}, y_{2s}, z_{2s})	(0,10,0)	(x_{2e}, y_{2e}, z_{2e})	(0,60,30)
m_3	3	(x_{3s}, y_{3s}, z_{3s})	(0,0,0)	(x_{3e}, y_{3e}, z_{3e})	(0,60,0)
m_4	1.8	(x_{4s}, y_{4s}, z_{4s})	(0,-10,0)	(x_{4e}, y_{4e}, z_{4e})	(0,60,-20)
m_5	0.8	(x_{5s}, y_{5s}, z_{5s})	(0,-20,0)	(x_{5e}, y_{5e}, z_{5e})	(0,60,-40)

TABLE1 PARAMETERS FOR DISASSEMBLY SEQUENCE EVALUATION

As previously said, the proposed method for evaluating the disassembly task by mechanical energy expenditure requires to measure angle θ_1 of the arm at the starting and ending point for all the components involved in the disassembly sequences. Kinect 2 was used to capture this angle and the data are as presented in Table 2.

Component	1	2	3	4	5
$\theta_{1i}^{t_0}$ (rad)	-0.550	-0.592	-0.627	-0.592	-0.550
$\theta_{1i}^{t_1}$ (rad)	0.500	0.159	-0.387	-0.429	-0.953

TABLE 2. ANGLE BETWEEN OPERATOR UPPER ARM AND HORIZONTAL FRAME LINE FOR STARTING AND ENDING POINT OF THE COMPONENTS

The values of h_{aiu} for each component, calculated according to equation (7) are presented in Table3.

component	1	2	3	4	5
h_{aiu}(m)	0.223	0.0837	0.025	0.006	0.158

TABLE 3. VALUES OF $\boldsymbol{h_{aiu}}$

According to the proposed model, the mechanical energy for performing the disassembly Sequence 1 and Sequence 2 are respectively: $\Delta E_{S1} = 41.87J$ and $\Delta E_{S2} = 24.66J$. It is seen that ΔE_{S1} is bigger than ΔE_{S2}. Based on Hypothesis 1, 2, 3 and 4, the results show that performing disassembly Sequence 1 (S1) induces more fatigue in the arm's muscles than performing disassembly Sequence 2 (S2).

IV. VIRTUAL REALITY ENVIRONMENT FOR FATIGUE DISASSEMBLY TASK EVALUATION

A. Experimental set up

In order to prove the proposed model, series of experiments were carried out in the Virtual Reality environment GINOVA platform, Grenoble-INP (National Polytechnic Institute). The task (divided in two sub-tasks T1 and T2) consisted in handling an electrical motor (weight of *1kg*.) in a restricted vertical space of *0.5m* with repetitive *bottom up* and *up down* movement during *5* minutes with low speed (frequency of *0.17 Hz* (*10* movements for one minute). The distance between subjects' eyes and the display screen is fixed at *2.25 m*.

The visual feedback (displacement of the motor in the VR screen) is the same as the displacement of the end of the hand in the real physical environment. In order to limit the amount of EMG signals treatment and consequently the number of muscles involved in the disassembly task, the latter was performed only by the lower arm of the subject (upper arm in static position: θ_1 constant).

Nine subjects, aged from *24* to *58*, were involved in the experiments. Unfortunately, the female subject did not endure until the end of the task, so the effect of different sex on fatigue has not been investigated in this stage of the study. Subjects declared no performed intensive muscle efforts during *24* hours period. All participants reported no history of problem in upper limbs. Since θ_1 is constant, when calculating the mechanical work, the task is performed when only the lower arm is moving.

The VR environment consists of (Fig. 3): - VIRTUOSE 6D35-45 haptic device with force feedback; Kinect tracking system; stereoscopic display; 3D glasses; four channels EMG *BIOPAC MP150* system.

The software used to generate the simulation environment is IFC (*Interactive Fitting for CATIA*) which is a CAAV5-based plug-in for CATIA V5TM for interactive simulations. The weight of the motor was simulated by the gravity environment in CATIA. Virtual objects in the software are constrained by gravity field. The force feedback, during collisions, is sent to the subject via the haptic device.

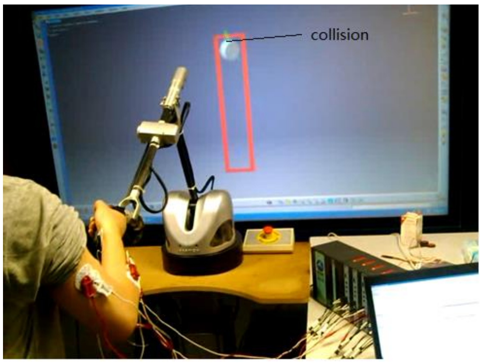

Figure 3. Environmental virtual reality environment

As previously said, the task was divided into *two sub tasks in order to* discriminate which one induces more muscle fatigue. The first *2.5* minutes period of vertical movements represents the task 1 (*T1*). The total *5* minutes period of the whole movement represents the task 2 (*T2*). Note, that T1 and T2 consist in the same repetitive *bottom up* and *up down* movement. In order to evaluate the muscle fatigue level on the subject forearm, subjects had to perform a MVC task before and after the test.

As previously said, during the task (subjects in standing position), the EMG signals on *extensor carpi radialis* (*ECR*), *flexor carpi radialis* (*FCR*), *biceps* and *triceps* were recorded. For this purpose SENIAM (surface EMG for non-invasive assessment of muscles) location protocol was used with four sets of electrodes of EMG *BioPac MP150* system. The signal from the electrode on the *ulnar styloid process* muscle was used as ground signal. The EMG signals for each subject have been normalized with EMG signals of each muscle detected during the task. After filtering, Fast Fourier Transfer (FFT) function was used to transfer the raw EMG signal. The power spectrum density of each muscle contraction was estimated by using Hamming window. The median frequency for each muscle contraction was approximated by straight line. Thus, bigger decreasing slope represents faster fatigue process.

B. *Results*

The *normalized EMG signals* define the power spectral density function (PSDF) which reflects the change of the frequency of EMG along with the time. Thus, after Short-Time Fourier Transform processing of the normalized EMG signals, the power spectral density function (PSDF) are obtained. Calculating the median frequency (MDF) in each window and connecting all the points of MDF allows to obtain a curve which is nearly linear (Fig. 4). MDF slopes have been used as fatigue index in process of maintaining isometric contraction.

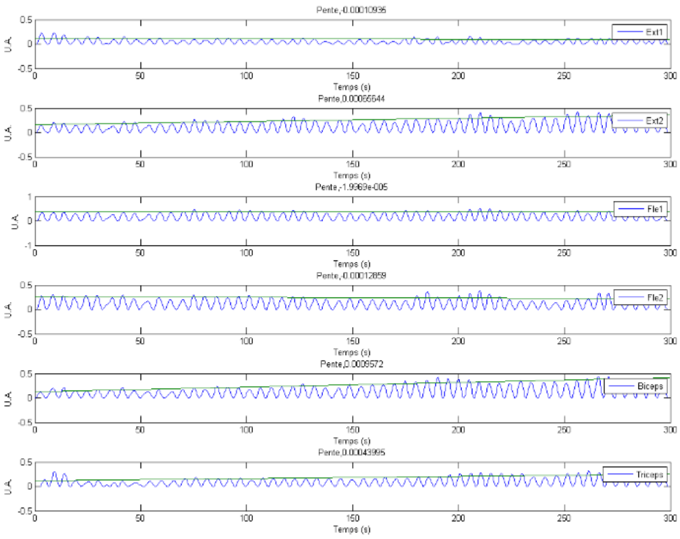

Figure 4. Power spectral density function (PSDF) for the involved muscles

The linearly decreasing slopes of each MDF line in the PSDF figures, which is indicator of the fatigue, are given in Table 4.

	1	2	3	4	5	6
slope	-0.213	-0.198	0.198	-0.083	0.227	-0.136

TABLE 4. SLOPE OF MDF LINE

Student *t* test analysis (unilateral Student *t* test, $\alpha = 0.05$) shown that a significant difference appears between *C* and *B* for *FCR* and *Biceps* muscles only (respectively *t=-1.848, t=-1.775*). No *significant* statistical difference was found between *A* (average of the RMS peak values of the first five muscle contractions for the involved muscles in *T2*,) and *B* (average peak value of last five successive muscle contractions of *T1*) for all the muscles, neither between *B* and *C* (average peak value of last five successive muscle contractions of *T2*) for *ECR* and *Triceps* muscles. Hence the fatigue induced by *T1* is less than *T2* as the average of *B* is lower than *C* in FCR and Biceps.The results indicated also that *T2* induced more fatigue than *T1*. It means that the task involves greatly flexor muscles (*FCR*, B*iceps*) with greater fatigue in *T2* than *T1* for those two muscles.

Table 5 shows the results of median frequency for *FCR* and *Biceps* muscles. It confirms that fatigue appears in both muscles. Moreover, slope values indicate that fatigue increases faster during the 2.5 first minutes (*T1*) than in the whole 5 minutes period (*T2*).

	T1 (2.5 minutes)	T2 (5 minutes)
FCR	-0,13003878	-0,06598795
BICEPS	-0,03164797	-0,0023069

TABLE 5. DECREASING SLOPE OF MEDIAN FREQUENCY OF EMG

C. *Discussion*

The results of the performed tasks in the VRE show that *Biceps* and *FCR* muscles are the prime movers involved. On the other hand, fatigue develops faster in the beginning of the task (first 2.5 minutes, T1) than for the whole 5 minutes time period (T2). This could be resulted from the fact that the anaerobic exercise of *fast twitch* is the activity mainly involved in the T1 task and the aerobic exercise of *slow twitch* is the principle muscle behavior in *T2* task. However, experimental results indicated greater fatigue in *T2* than in *T1*.

In order to prove the validity of the proposed mechanical model, it was applied to calculate the mechanical energy expenditure in *T1* and *T2* performed in the VRE. The values of the mechanical energy expenditure are respectively $\Delta E_{T1} = 308\,J$ and $\Delta E_{T2} = 616\,J$. Thus, according to the proposed methodology, the fatigue developed in *T2* is bigger than in *T1*, which is in agreement with the experimental results.

In order to compare fatigue for different disassembly tasks, the associated mechanical energy expenditure values are calculated here by the proposed mechanical model.

From the aspect of loading level, since the gravity forces of the components were simulated, it is the same as in the real world. From the aspect of operation method of haptic device, it only allows simulating a single hand operation by holding the handler of the VIRTUOSE haptic device.

The main application field of the results of this paper is to enable designers to compare the fatigue levels associated with different disassembly tasks simulation performed in VR environment.

V. Conclusion

This paper introduced a new method for disassembly task evaluation which aims at using the expenditure volume of metabolic energy to quantify fatigue.

The proposed method is more efficient than the method of Bisi et al. [11] which requires so much data necessary for predicting metabolic energy consumption and consequently fatigue evaluation.

The method is based upon four hypothesizes and proved by experimental tests. Thus, Hypothesis 1 has been proved from the theoretical derivation and the experimental results.

The agreement between the theoretical results and experimental ones indicated that the proposed method is pertinent for estimating the level of peripheral fatigue induced while performing a disassembly task in VRE. The analysis of the median frequency of EMG signals proved the existence of fatigue in the involved muscles. Another interesting result is that subjects fatigue happens faster in *T1* (beginning of the task) than in *T2*.

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