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▶ To cite this version:

Peter Mitrouchev, Jingtao Chen, Sabine Coquillart, Franck Quaine. Disassembly Task Evaluation in Virtual Reality Environment. Research and Science Today, Research and Science Today, 2017, 84 (suppl. 2/2017), pp.84-91. hal-01686745

HAL Id: hal-01686745
https://hal.archives-ouvertes.fr/hal-01686745

Submitted on 18 Jan 2018

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DISASSEMBLY TASK EVALUATION IN VIRTUAL REALITY ENVIRONMENT

Peter MITROUCHEV[1], Jingtao CHEN[1]
Sabine COQUILLART[2]
Franck QUAINE[3]

ABSTRACT:

The influence of Virtual Reality (VR) on human behavior with using biomechanical analysis methods and its application for assembly/disassembly operations simulation is presented in this paper. A new haptic model for mechanical energy expenditure is proposed where the required mechanical work is used as main parameter. The fatigue levels are evaluated by analyzing the recorded electromyography (EMG) signals on the most involved muscles of operator's arm. A set of experimental disassembly tests realized in a VR environment are performed thus allowing to validate the proposed method. 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.

KEY WORDS: virtual reality environment, muscle metabolic energy, disassembly sequences evaluation, muscle fatigue, mechanical energy

INTRODUCTION

Assembly/Disassembly (A/D) operations simulations represent important research subject today. With the new European and International sustainable legislation these operations are often considered in the initial stage of product design. Thus, in order to evaluate disassembly sequences different tools and Virtual Reality (VR) human-computer interfaces (HCI) are proposed [4]. The VR set-up can be easily modified allowing designers to quickly adjust the design of product. Ppreliminary evaluation of disassembly sequences during product design being a very important issue 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 simulation. Thus, a new method for evaluating the hand fatigue associated with disassembly task by utilizing metabolic energy expenditure is proposed here. Note, that before displacement, the components/modules linked by fasteners (screws, clips) have to 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. Disassembly experiments in VR were performed in order to evaluate fatigue with electromyography (EMG) analysis. The proposed 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. According to the proposed protocol, during the disassembly task (subjects in standing position), the EMG

[1] PhD, Univ. Grenoble Alpes, CNRS, Lab. G-SCOP, Grenoble, France, Peter.Mitrouchev@grenoble-inp.fr, Jingtao.Chen@grenoble-inp.fr
[2] Prof. Univ. Grenoble Alpes, CNRS, INRIA-LIG, Grenoble, France, sabine.coquillart@inria.fr
[3] PhD, Univ. Grenoble Alpes, CNRS, GIPSA-Lab, Grenoble, France, Franck.Quaine@gipsa-lab.grenoble-inp.fr

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 and then analyzed. This capture of muscular contractions is the reason to limit the observed movements in quasi-static motion. For this reason, 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.

RELATED WORK

Today some approaches for VR disassembly evaluation are proposed by taking into account different criteria such as*: i).* visibility score [12], *ii).* set of directions for removal (SDR) [5], *iii).* stability of sub-assembly [6], i*v).* number of tools [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. In order to avoid uncertainty of disassembly operation process, Tian et al. [11] 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. Bisi [1] proposed an EMG (Electromyography) *driven model* for predicting metabolic energy consumption during physical effort which includes EMG signals from active muscles associated with some kinematic joint parameters. However, the model is too complex and time consuming to predict its metabolic energy consumption which requires a motion capture analysis system coupled with EMG data processing. Rube and Secher [9] proved that the neural adaption of muscles may by activated by changing their activation mode. In [7] it was mentioned that the effect of training on fatigue depends on training mode. 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 [8]. It was proven [10] that the peak value of EMG signals after root mean square (RMS) processing is also an index of fatigue [2]. Thus, a new method of predicting the fatigue during disassembly task in VR environment is proposed here.

METHOD

In the proposed method it is assumed that [3]: *i).* more mechanical energy is required to complete the disassembly task, more metabolic energy will be consumed in the human arm, *ii).* the arm muscles, involved in the disassembly task, perform in an environment with constant temperature, *iii).* the task is performed in continuous way, *iv).* he fatigue accumulated in the muscle is a monotonically increasing function of the metabolic energy expenditure, *v).* during the disassembly task, the operator, in standing position, is moving the virtual objects with a given velocity in all allowed disassembly directions, *vi).* 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*. The fatigue is presented as $FA = f(FA_c, FA_p)$, where FA_c and FA_p are respectively the fatigue in central nervous system and peripheral system (muscle). The 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: $FA_p = f[E(F,t,v)]$ 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. The muscle mechanical model we presented in [3] shows that the maximal muscle fatigue may be reached for different values of *F*, *t* and *v*. Suppose that there are *n* components to be disassembled in sequence *S* (task). Thus, the mechanical energy expenditure for moving the operator's arm is: $\Delta E_{S1} = \sum_{i=1}^{n}[m_i g(h_{iu} + h_{id}) + 2m_a g h_{aiu}]$ 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 i-th 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. We model the arm as a two DOF (degrees of freedom) mechanism with three segments as shown in Fig. 1.*a* where the first segment, the operator's body, is supposed to be its frame. Gravity is defined as –**Z**.

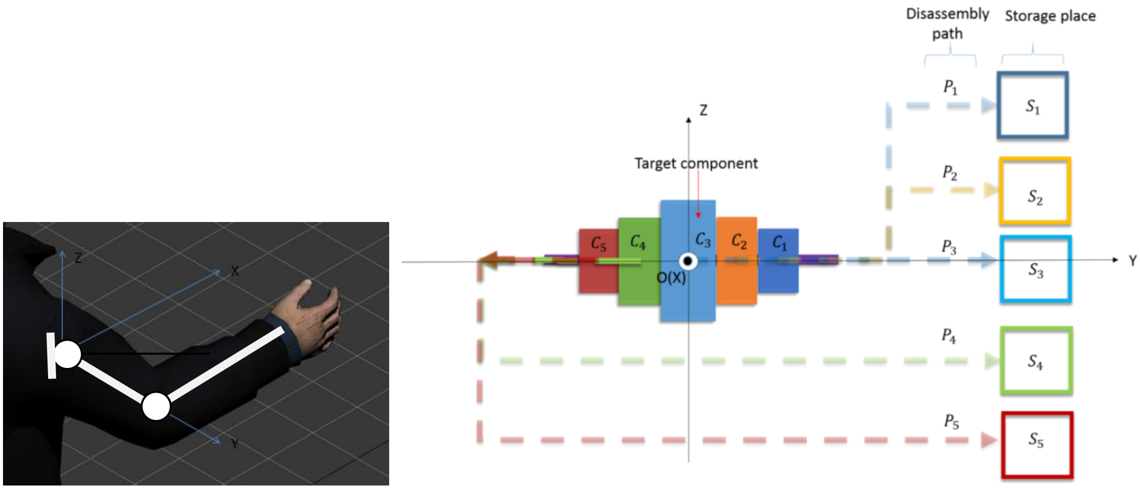

Figure 1. a). Operator's arm with its associated two joints mechanism, b). Mechanical assembly and parts' trajectories for disassembling target component $\boldsymbol{C_3}$

In the proposed method we also assume that the shoulder only rotates around ***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. Note that for disassembling some components specific tools may be required. Consequently, they are considered as ordinary disassembly components moved by the operator. 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 (Fig. 3) that limits the proposed method of one point loading (weight in the mass center of the wrist). 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.

The analytical model for evaluating the fatigue induced during disassembly sequence simulation is illustrated by an example of a simple disassembly manufacturing process. It consists in disassembling a five component mechanical assembly where the target component is component *3* as presented in Fig. 1.b. Each component ($C_1, C_2 \ldots C_5$) is moved from its initial position to storage place ($S_1, S_2 \ldots S_5$) following the corresponding disassembly path ($P_1, P_2 \ldots P_5$). For disassembling the target component C_3, for instance, there are two possible disassembly sequences: Sequence S1= $\{C_1, C_2, C_3\}$ and Sequence S2= $\{C_5, C_4, C_3\}$.

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 the hypothesis, the results show that performing disassembly Sequence *1* (*S1*) induces more fatigue in the arm's muscles than performing disassembly Sequence *2* (*S2*).

VIRTUAL REALITY ENVIRONMENT FOR FATIGUE DISASSEMBLY TASK EVALUATION

Series of experiments were carried out in the Virtual Reality environment GINOVA platform, Grenoble-INP (National Polytechnic Institute) in order to prove the proposed model. 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 displacement of the motor in the VR screen (visual feedback) 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. In the experiments nine subjects, aged from *24* to *58*, were involved. 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. When calculating the mechanical work, the task is performed when only the lower arm is moving. The VR environment consists of (Fig. 2): *VIRTUOSE 6D35-45* haptic device with force feedback; Kinect tracking system; stereoscopic display; 3D glasses; four channels EMG *BIOPAC MP150* system. The simulation environment IFC (*Interactive Fitting for CATIA*) 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.

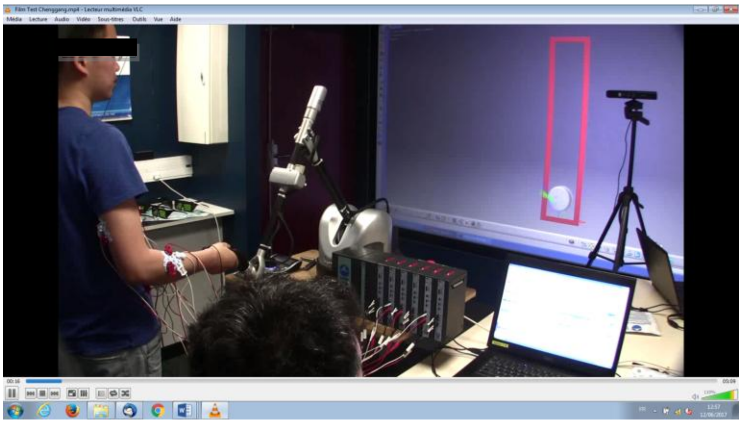

Figure é. Virtual reality environment setting

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 maximum voluntary contraction (MVC) task before and after the test. The EMG signals on *extensor carpi radialis* (*ECR*), *flexor carpi radialis* (*FCR*), *biceps* and *triceps* were recorded during the task (subjects in standing position). 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. 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. MDF slopes have been used as fatigue index in process of maintaining isometric contraction. The linearly decreasing slopes of each MDF line in the PSDF figures, which is indicator of the fatigue, are given in Table 1.

Table 1. Slope of MDF line

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

Student *t* test analysis (unilateral Student *t* test, α =*0.05*) shown that a significant difference appears between average peak value of last five successive muscle contractions of *T2* (*C*) and average peak value of last five successive muscle contractions of *T1* (*B*) for *FCR* and *Biceps* muscles only (respectively *t=-1.848, t=-1.775*). No *significant* statistical difference was found between average of the RMS peak values of the first five muscle contractions for the involved muscles in *T2* (A), and *B* for all the muscles, neither between *B* and *C* 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. 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*. The validity of the proposed mechanical model was proved by its application 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. The associated mechanical energy expenditure values are calculated by the proposed mechanical model in order to compare fatigue for different disassembly tasks. Since the gravity forces of the components were simulated, the loading level 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 study is to enable designers to compare the fatigue levels associated with different disassembly tasks simulation performed in VR environment.

CONCLUSION

The paper introduced a new method for disassembly task evaluation which aims at using the expenditure volume of metabolic energy to quantify fatigue. It is more efficient than the method of Bisi *et al.* [1] which requires so much data necessary for predicting metabolic energy consumption and consequently fatigue evaluation. The method is based upon six hypothesizes and proved by experimental tests. 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*.

Acknowledgment: This work has been partially supported by the LabEx PERSYVAL-Lab (ANR--11-LABX-0025) » (http://www.persyval-lab.org/index.html)

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