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In ergonomics, digital mock-ups of workstation design in virtual reality environments are often used to evaluate the occupational risks related to a working condition. However, the effectiveness of such technology, particularly in terms of human performance can be questionable. In the present study, we investigated the pattern of movement variability in a simulated assembly task and presented an index of task performance that can highlight the differences in terms of motor control strategy between a real assembly task and its virtual simulation. The movement variability was decomposed into goal-equivalent and non-goal equivalent components and the ratio of these components was introduced as an index of performance. The ratio was greater in the real than in the virtual environment. This study highlights the differences in terms of motor control strategies in real and virtual environments.

Practitioner Summary: A simulated assembly task was implemented in a real and a virtual environment. A performance index in light of the motor control theory was introduced. This index could discern a lower performance in the virtual compared with the real environment. The developed approach can provide an objective index to investigate the system fidelity in virtual environments.

Keywords: Goal-relevant and non-goal-relevant variability, biomechanical response, task performance, uncontrolled manifold, multi-joint movement control

1. Introduction

The virtual reality (VR) technology has found numerous applications in industrial design as it can provide intermediary decision support tool to satisfy multidisciplinary viewpoints and optimize the design process for a wide range of applications (Bennes et al. 2012). Especially in the case of manufacturing process design, it opens a wide range of perspectives to enhance the collaboration between the actors of the design, reduce the costs and optimize the work conditions without depreciation of the productivity features (Pontonnier et al. 2013; Pontonnier et al. 2014a).

However, in Ergonomics, VR interfaces are yet to be assessed and optimized, in particular, determining the effectiveness of VR interfaces in light of the human performance poses a challenge (Pontonnier et al. 2014b; Stanney et al. 1998). For example, when VR interfaces are used to design a manufacturing process, the assessment of biomechanical characteristics of the performed task and ergonomics considerations are crucial (Mujber et al. 2004). In particular, pinpointing the differences between the real and VR environments will help designing improved VR environments with higher preservation of biomechanical response. This, in turn, improves the validity of the knowledge learnt from VR environments and the ergonomics decisions adopted based on the acquired knowledge. For example, assessing the human movement from a motor control point of view will shed light on the possible differences between the real and VR environments.

The human movement literature proposes analysis methods which are of potential interest to assess the human performance in VR environments (Latash et al. 2007). Despite the availability of such methods, to our best knowledge, no study has compared multi-joint movements performed in VR environments and those in the real world from a motor control perspective. Particularly, in light of the human performance, motor control strategies can be revealed in the structure of motor variability when similar movements are repeated (Latash et al. 2002). This implies that variability in the elemental biomechanical variables (e.g. joint angles) can be decomposed into goal-equivalent (GE) and non-goal equivalent (NGE) components where the former one represents the variability of the elemental variables in a subspace that does not compromise the performance whereas the latter term does (Tseng et al. 2002). In other words, the motor control system allows the variation of GE component in a subspace called uncontrolled manifold (UCM), therefore, a higher GE than NGE implies a stable control of the performance (Latash et al. 2002).

The motor variability decomposition is essentially interesting to be studied in VR environments as the visual fidelity of a VR display is typically low compared with physical reality (Sanchez-Vives and Slater. 2005) and the alteration of visual feedback has been shown to affect the GE and NGE terms (Ranganathan and Newell. 2008).

Further, investigating GE and NGE terms of motor variability may provide assessment of human performance in VR environments. For instance, the ratio between the variability terms can indicate the proportion of inherent motor variability which would be directed towards the performance stabilization (Domkin et al. 2005). Such an index allows us to assess the effect of improved technologies in the VR world and the changes in performance due to learning effect and any other attributes of the tasks (e.g. precision demands) performed in VR setups. For example, the biomechanical responses in VR environments have been shown to be affected by the task attributes (Pontonnier et al. 2014b; Samani et al. 2015; Stoffregen et al. 2003) even though this has never been thoroughly investigated in terms of motor variability.

We compared the GE and NGE motor variability during a simulated real task and a similar virtual task performed with a high level of fidelity. We hypothesized that the ratio of GE and NGE is greater during performing a multi-joint real task compared to its similar virtual version as it indicates that a greater proportion of variability is directed toward the performance in real environment. This could potentially be used as a novel approach to study the human performance in VR environments.

2. **Methods**

Sixteen male participants (mean ± SD, aged 26.5±2.8 years; height 178.4±6.5 cm; body mass 70.2±9.2 kg) took part in the present study. All participants reported no history of neck-shoulder disorders and were all novices in VR (average experience of 1.4±0.5 on a 5-point scale anchored with “1: Novice” and “5: Expert”). The study was conducted in accordance with the declaration of Helsinki, and was approved by the local ethics committee. The participants signed an informed written consent prior to the experiment.

2.1 Experimental procedure

The participants performed a simulated task within two different platforms, i.e., a real (RE) and a virtual (VE) platform. The task was a simplified assembly task and consisted of target reaching, object manipulation and sorting with standing posture. A detailed description of the working station can be found in our previous work (Pontonnier et al. 2014b). Twelve wooden objects should have been taken from a storage shelf and then passed through the holes of a work panel (“fitter” objects) or placed on a disposal shelf (“non-fitter” objects). The work panel was located on a table set at the elbow height. The storage and disposal shelves were 40 cm above the table surface and 16 cm to the left and the right of the work panel centre, respectively.

The participants performed one trial within each platform with at least 2 min rest between them. During a trial the participants moved their hands toward the storage shelf and grasped an object and placed it in the work panel (“fitter”) or on the disposal shelf (“non-fitter”). There were equal number of fitters and non-fitters in each trial. The handling of “fitter” objects demanded a higher precision than that of “non-fitter” objects. The order of the platforms and object type (“fitter” and “non-fitter”) were randomized.

The interaction with the VE was done with a wireless stick (Flystick2, Advanced Real time Tracking GmbH, Germany) co-localized with the virtual scene. The grasping was done by a trigger button actuated with the forefinger and the thumb in VE and only one active and visible object was displayed on the storage shelf at the time of grasping.

2.2 Data recordings

Clusters of reflective markers were placed on the lower trunk, upper trunk, head (glasses), right arm, forearm, and hand and the orientations of these body segments were tracked in 3D using six dedicated AR-Tracking targets, sampled at 60 Hz (Pontonnier et al. 2014b). A simplified kinematic model was used to obtain the Cartesian relative rotation matrices of the connected body segments with respect to each other (Pontonnier and Dumont. 2009a). A simple identification of the joint coordinates was performed from the rotation matrices on the basis of the functional degrees of freedom (DOF) (Kapandji. 1987; Pontonnier and Dumont. 2009b). Figure 1 depicts the applied model and the DOF in each joint. The rotation angles were obtained with respect to a reference standing position with both arms along the body. The lengths of the segments were initially evaluated on the basis of Dempster's anthropometric laws (Dempster. 1955) and then adjusted by minimizing the difference between the recorded position of the hand and the head and their corresponding reconstructed ones using the segments' lengths.

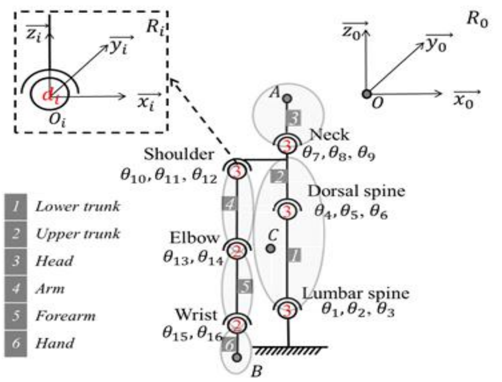

Figure 1. Kinematical model associated to the upper limb, head and trunk motions. d_i indicates the number of degrees of freedom associated with the joint i located in O_i and associated with the frame R_i. Points A, B and C represent respectively the mid-eye position, the hand centre position and the {trunk+head+upper limb} centre of mass position.

The global centre of mass (CM), denominated here as the performance index P_t, was computed as:

$$P_t = \sum P_{t_i} m_i$$

Where P_{t_i} is the CM position of the i-th segment relative to the reference frame of the segment and m_i is the percentage of mass represented by this segment, according to De Leva tables (De Leva. 1996). The tracking system tracked the hand position with a dedicated cluster of optical markers. A cycle was determined from the time of moving the hand towards the object until the object was passed through the work panel ("fitter") or placed on the disposal shelf ("non-fitter").

2.3 Data analysis

The cycles were sorted into the six "fitters" and six "non-fitters" cycles and the trajectories were interpolated such that 200 samples represented the trajectories across one cycle. A reference joint angle trajectory per "fitters" and "non-fitters" was calculated by averaging the trajectories across the cycles at each time point. The variability across the cycles was decomposed into GE and NGE components using uncontrolled manifold technique (Scholz and Schöner. 1999).

A forward kinematic model described an analytical relationship between the joint angles $\vec{\Theta}$ and the performance index which in this study was considered to be the CM of the upper body. We assumed that the motor control system co-vary the joint angles to stabilize the performance index. The analytical relationship between the performance and the joint angles can be linearized around the reference trajectory at each time point.

$$P_t - P_{0_t} = J_{\vec{\Theta}_{0_t}} \left(\vec{\Theta}_t - \vec{\Theta}_{0_t} \right) = J_{\vec{\Theta}_{0_t}} \overrightarrow{\Delta\theta}_t \qquad \text{Equation 1}$$

Where P_t , P_{0_t}, $\vec{\Theta}_t$ and $\vec{\Theta}_{0_t}$ and are the performance index (P) and the joint angles ($\vec{\Theta}$) and their corresponding values at the reference trajectory, respectively. In the current study, P_t and P_{0_t} have three dimensions (d=3) corresponding to the spatial position of the CM and 16 variables determining the joint angles (n=16). $J_{\vec{\Theta}_{0_t}}$ is the Jacobian matrix which quantifies the variation of performance index with respect to each of the joint angles and has 3 rows and 16 columns corresponding to the performance index and the joint angles, respectively.

The GE component of movement variation across cycles was the term which does not compromise the performance. Thus, the right side of Equation.1 must be zero and this was satisfied if $\overrightarrow{\Delta\theta_t}$ lied in the null space of the Jacobian matrix. Thus, the projection of $\overrightarrow{\Delta\theta_t}$ into the null space reflected a term of variability which did not affect the performance. The projection was calculated by multiplication of $\overrightarrow{\Delta\theta_t}$ and the basis of the null space $\vec{\varepsilon}_i$ which can be obtained numerically (Axler. 1997). Hence, we wrote:

$$D_{GE_t} = \sum_{i=1}^{n-d} (\vec{\varepsilon}_i^T . \overrightarrow{\Delta\theta_t}) \vec{\varepsilon}_i$$

and the NGE component was derived from the subtraction of GE component from $\overrightarrow{\Delta\theta_t}$, i.e., $D_{NGE_t} = \overrightarrow{\Delta\theta_t} - D_{GE_t}$. Subsequently, the square of calculated V_{GE_t} was averaged across the cycles and normalized to the number of dimension in each subspace to derive GE and NGE components.

$GE_t = \frac{\sum_{cycles} D_{GE_t}^2}{N_{cycles}(n-d)}$, $NGE_t = \frac{\sum_{cycles} D_{NGE_t}^2}{N_{cycles}(d)}$ and the total variance normalized by the dimension number would be $Total_t = \frac{\sum_{cycles} \overrightarrow{\Delta\theta_t}^2}{N_{cycles}(n)}$ and $Rv_t = \frac{GE_t}{NGE_t}$ as an index of stabilization (Domkin et al. 2005).

2.4 Statistics

Object type and platforms were introduced as within-subject factors in a full-factorial repeated measure analysis of variance for the mean of GE_t (GE), the mean of NGE_t (NGE), the mean of $Total_t$ (Total) and the mean of Rv_t (Rv) across the time line of a cycle. The within subject independent factors were platforms (RE and VE) and Object type (fitter and non-fitter). A similar test has also been performed to compare GE and NGE. In all tests, P<0.05 was considered significant.

3. Results

The time line of GE_t and NGE_taveraged across subjects in RE and VE environments are depicted in figure 2. GE was larger than NGE for both platforms as well as both object types (p<0.03). This can also be seen throughout a cycle in figure 2.

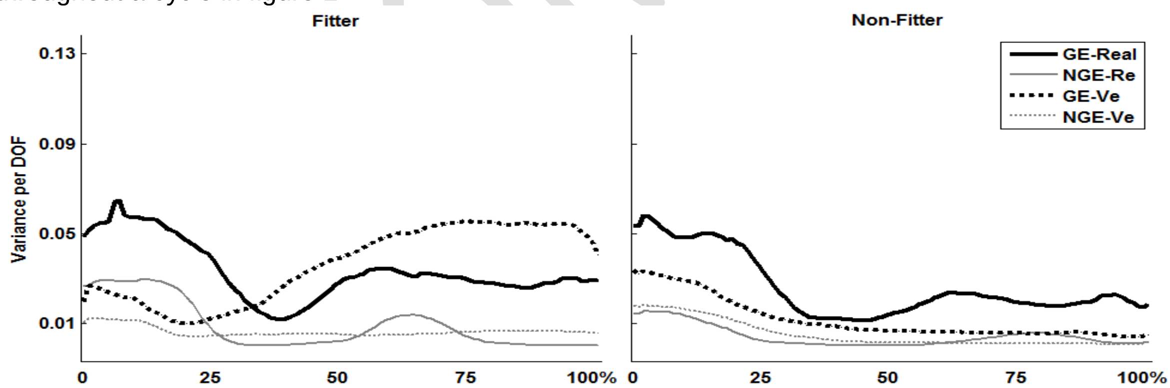

Figure 2. The average (across subjects) of time line of the goal-equivalent (GE; thick line) and the non-goal equivalent (NGE; thin line) component per degrees of freedom (DOF) during a repetitive simulated assembly work in real (RE; solid line) and virtual (VE; dashed line) and for both object types (fitters on the left and non-fitters on the right). The confidence interval around each curve has not been included to avoid confusion in the illustration of the figure.

Platform played a significant role on the Rv ($F_{1,15}$=56.8, P<0.001). Rv was smaller for VE than RE. Object type played a significant role on NGE ($F_{1,15}$=11.4, P=0.004 and $F_{1,15}$=33.7). NGE was greater for fitter objects than non-fitters. The interaction of platform × object type also played a significant role on GE and Total ($F_{1,15}$=17.3, P=0.001 and $F_{1,15}$=14.8, P=0.002, respectively) but it only tended to play a significant role on NGE ($F_{1,15}$=4.4, P=0.05). GE and Total were greater in RE only for non-fitter objects but NGE was larger in RE for fitter objects. Further, GE and Total were greater for fitters only in VE environment but NGE was greater for fitters only in RE environment. Figure 3 shows GE, NGE and Total for each of the platforms and object type and Rv is depicted in figure 4.

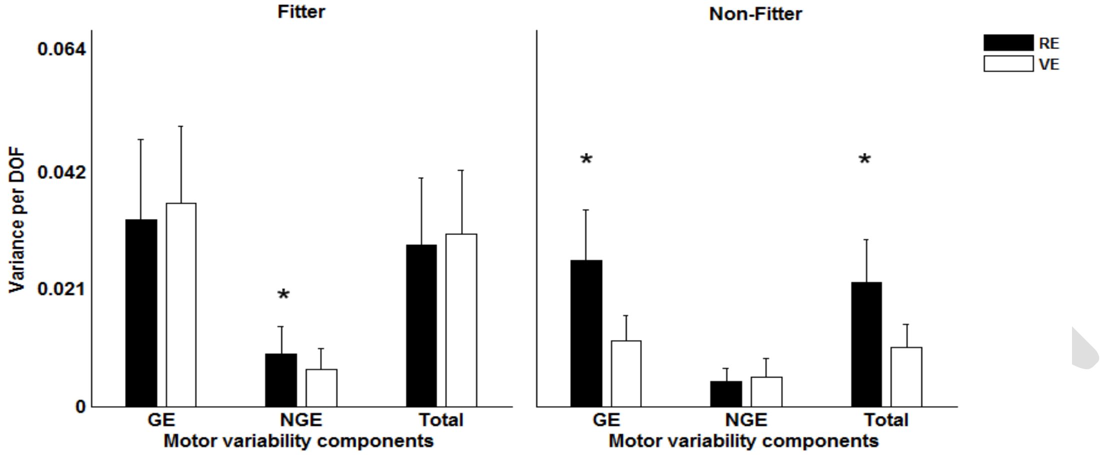

Figure 3. The mean ± SD of the goal-equivalent (GE), the non-goal equivalent (NGE) variance components and the total variance per degrees of freedom of repetitive simulated assembly work in real (RE) and virtual (VE) and for both object types (fitters on the left and non-fitters on the right).

4. Discussion

The framework of UCM was used to assess the kinematic synergy during a multi-joint cyclic movement in a real and virtual environment. The movement variation was decomposed into its GE and NGE components. As expected, CM revealed a stabilized pattern reflected in higher GE compared with NGE in both platforms and for both object types. However, CM revealed an improved stabilization in RE compared with VE whose Rv was smaller than that of RE. The object type affected the total variability across cycles as Total was greater for fitter objects compared with non-fitters but only in VE. Interestingly, the increased variability for fitter objects in VE was mainly directed into GE component by the motor control system as higher GE was observed for fitters compared with non-fitters in VE.

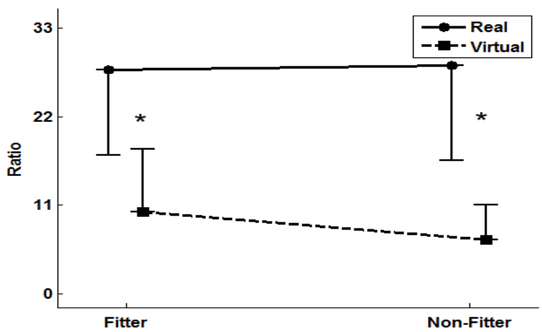

Figure 4. The mean ± SD of the ratio of the goal-equivalent (GE), the non-goal equivalent (NGE) variance components and the total variance per degrees of freedom of repetitive simulated assembly work in real (RE) and virtual (VE) and for both object types (fitters and non-fitters). The ratio represents an index of the stability of the centre of mass.

We have recently found that the potential risks posed by posture for neck-shoulder musculoskeletal disorders are different in real and virtual platforms (Pontonnier et al. 2014b). However, we had not addressed the differences between the two platforms in terms of movement control. When studying voluntary multi-joint movements, one paramount issue is always raised and that is how the motor control system handles redundant DOFs (Latash et al. 2007). Conventionally, it is believed that the motor control system search for a unique and optimal solution and freezes the redundant ones (Seif-Naraghi and Winters. 1990), however, more recent studies suggest that the motor control system facilitate families of the solutions that are equally able to achieve the movement goal (Scholz et al. 2000). This converts a redundancy problem to an abundance problem in which the role of motor control system is not to eliminate the DOFs but to organize them.

According to the notion of DOF abundance, the motor control system can allow co-variation patterns of elemental variables (e.g. joint angles) such that the task performance is not compromised. Conversely, the control system should restrict co-variation patterns that affect the task performance. Thus, GE component of variation is expected to be greater than NGEV and their ratio (Rv) could be seen as a stability index of the task performance (Domkin et al. 2005).

Along with such a premise, we observed that GE was greater than NGE in both platforms and for both objects types. It is interesting that even in cases where the Total variance did not show a significant difference between the two platforms, a larger proportion of variance was directed to the GE subspace than NGE. A higher Rv in RE compared with VE indicates that the subject performed the task in RE while they had a more stable upper body (i.e. CM) compared with VE.

In this study, CM was considered as the performance index of movement dynamics as some studies point at the importance of this variable in tasks such as reaching movement and argue that CM is even more stabilized than the end-effector position (Suzuki et al. 1997) even though this point has also been criticized (Scholz et al. 2000; Tseng et al. 2002). Our study proposes that regardless of this debate, Rv could be used as index of performance in VE when it is being compared to the real ones.

It is conceivable that the visual feedback is changed in VE and visual feedback is known to be crucial in movement planning and control (Carlton. 1981). Thus, the differences between VE and RE platform can be related to a manipulated visual interface in VE. However, the absence of vision has been reported to affect the movement coordination only when the task is being performed with low hand dexterity but not when the task is performed with the dominant hand (Tseng et al. 2002). Although the participants in the current study were novice users of virtual environments, the performed task was fairly simple to execute and the subjects performed the task smoothly after familiarization.

It is believed that increasing the accuracy of a task result in tightening the margins of the task constraints and therefore the movement variability will reduce (Kudoh et al. 1997). Particularly, this has also been shown in terms of GE component of variability (Tseng et al. 2003). That being so, we expected to observe lower variability for fitter objects than non-fitters, however, we found that the GE and Total component of variance were greater for fitter objects compared with non-fitters and interestingly this was only in VE. A higher NGE was observed for fitter objects than non-fitters only in RE.

These seemingly contrasting results with respect to the literature of motor control may have simply been resulted from the geometrical structure of the work panel in which the target point (the hole on the work panel) differs for the fitter objects depending on their cross-sectional contours. This is still interesting that this extrinsic factor of increased variability (i.e. different target points) has been mainly observed in VE and the increased variance was mainly associated with GE. This may be due to technical issues that the work panel in the VE has slightly more relaxed constraints to accommodate the objects inside the work panel holes compared with the physical panel in RE.

As a computational limitation of the current study, the number of cycles of handling fitter or non-fitter objects is lower than what has been usually used to calculate GE and NGE. Although no theoretical lower limit has been mentioned, (Scholz et al. 2000) set a minimum 10 cycles in their study and in a few other studies 20 cycles have been used to perform the analysis (Domkin et al. 2005; Tseng et al. 2002). Nevertheless, our results can still highlight the differences in the task performance in real and virtual environments.

Finally we can conclude that during performing the repetitive arm movement presented here, it seems that the participants could perform the task while they had a more stable control over their body (i.e. CM) in the RE compared with the VE. All in all, the current findings warrants further research to establish a standard approach to compare the task performance related to ergonomics in real and virtual environments.

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