Evaluation of Fatigue Measurement Using Human Motor Coordination for Gesture-Based Interaction in 3D Environments

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Abstract. Benefits of immersive three-dimensional (3D) applications are enhanced by effective 3D interaction techniques. While gesture-based interaction provides benefits in these types of environments users commonly report higher fatigue than with other interaction solutions. Typically, fatigue is measured subjectively but may lack precision, consistency and depth. Our research proposes a novel, more consistent and predictable measure of fatigue. This paper presents the details of our technique based on human motor coordination, the results of an experimental study on gesture-based interaction, identifies attributing causes for fatigue and outlines design guidelines to reduce fatigue for gesture-based interaction techniques. These results have implications for gesture-based or mid-air interaction techniques for 3D environments, such as virtual environments and immersive visualizations.

1 Introduction and Motivation

Gesture-based interaction is an input mechanism used to interact with computer systems, it is intuitive to the users and effective for large display interactions [1]. There are several advantages expected when using hand-based gestures for interaction [2], for example:

- *Natural interaction:* Natural means for manipulation of virtual objects.
- *Direct interaction:* Controller-free environment where no additional devices are required to interact with the system.
- *Multiple uses of interaction:* For a spatial context, a hand movement can provide both positional values as well as the intended action by just using one hand gesture.

Regardless of its advantages, researchers still face the problem of creating applications that have all the former benefits. The designers of gesture-based interaction work based on application requirements to create new interaction gestures, this limits the exploration stage to understand about limitations and represent a drawback in this field. Therefore, the process of implementing a gesture for an application becomes rigid and may result in unfavorable designs.

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User studies about hand gesture interaction have revealed that hand/arm fatigue is one of the major drawback in this kind of interaction [3]. They did not addressed how the fatigue measuring tool was used, neither given suggestions to alleviate the fatigue experienced by the users. Our research study aims to use the understanding of human motor coordination to find a new approach of measuring and to explain the contributors to fatigue in gesture interaction.

We propose a novel measurement technique for contributing factors of fatigue. Combining a 3D environment with gestures interaction we present an experimental study to evaluate our measurement technique and validate it against others.

In this study we answer the following questions: (a) Is Continuous Relative Phase (CRP) measure a good way to find precise information on fatigue for hand gestures? (b) Based on the calculated CRP values, what is the pattern that can be used for hand coordination while the users perform the gestures? (c) Can CRP values validate the subjective data reported by users through questionnaires and NASA-TLX?. Our hypotheses were: (a) Our technique will report similar levels of fatigue as standard NASA-TLX. (b) Our technique will provide some information and help to determine the cause of fatigue in the field of gesture design.

2 Related Work

2.1 Measurements of Fatigue

In studies where fatigue was reported users were interviewed, asked to fill out questionnaires and rate their fatigue level according to predefined Borg's scales [4] or NASA-TLX. These metrics lack details about the contributing factors that could cause fatigue and are subjective because they could have variations between users according to their tolerance level. Chung et al. [5] designed a computer based body postural stress evaluation system that take the body joint range of motion and uses the neural network results to predict the workload. In a research conducted by Kölsch et al. [6], a comfort function for gestures design was created. However, this function had a limitation of area of application: horizontal area in front of the body. An objective measurement for muscle movements is electromyography (EMG). It can be used to measure muscle fatigue by recording signals and monitoring changes of different frequencies. The problem with this method is that gesture interactions don't usually have a long duration [1,2], therefore, it reduces the chances of getting enough muscle movement activity to record EMG signals for evaluating muscle fatigue. A similar issue results from the Cybex Text [7], which measures muscle contractions while subjects perform repetitive task until the movement force falls below 50 %.

2.2 Coordination Patterns

For any two joints, a coordination pattern can be represented in continuous relative phase (CRP). This describes the mechanical behavior of two joints using a single variable representing elements related to coordination. It is a function of time showing relative phase angles of a pair of joints throughout the entire movement cycle [8]. The phase angle is calculated using Eq. 1, where $x'(t)$ is the velocity and $x(t)$ is position at time t.

$$\phi(t) = \tan^{-1}\left(\frac{x'(t)}{x(t)}\right). \tag{1}$$

After normalizing the displacement and velocity data obtained from each joint, CRP can be calculated by subtracting the phase angle of one joint from the angle of the other joint, at the same instant throughout the movement cycle [9,10]. The formula to calculate the CRP angle of the lefthand/righthand joint pair is:

$$CPR(t) = \phi_{lefthand}(t) - \phi_{righthand}(t). \tag{2}$$

where $\phi_{lefthand}(t)$ and $\phi_{righthand}(t)$ are the normalized phase angles of the wrist and elbow respectively.

Coordinated movements can be either in-phase (simultaneous contraction of homologous muscles) or anti-phase (simultaneous contraction of non-homologous muscle) when the CRP value is 0° or 180° respectively. The stability of the wrist movement can be represented by the standard deviation for CRP values close to 0, which suggests how well the bimanual coordination pattern can be maintained. As the joint movement approach out-of-phase movements, the instability increases, which may affect the ability of muscle joints to withstand the movement impact [11]. These research findings have only been used in kinematics.

3 Fatigue Measurement Technique

3.1 Relation Between Fatigue and CRP

Calculating CRPs during the entire movement cycle for any two joints, we can evaluate the variability of CRPs from in-phase or anti-phase. Our work focuses on hand coordination by looking at the mean relative phase for the *lefthand - righthand* (distal) joint pair as a function during the movement cycle. The reason to consider this is because distal joints adjust the motion in order to continue with the movement cycle. During fatigue, coordination has been mostly characterized by a strong increase in the wrist movement to compensate proximal joint control impairment [12]. CRP values are represented in a range between 0° to 180° [8]. Our research aims at finding whether the variability measure of CRP for a gesture indicates fatigue during the movement. Using the commonly subjective tools to gather information on fatigue from users we can validate our approach on finding fatigue factors.

4 Experimental Study

To validate our technique, we conducted a research study at the 3-Dimensional Interaction and Agents (3DiA) Laboratory, using a $2 \times 2 \times 5$ mixed study design.

The study encompassed a between-subjects condition, where participants were assigned to one of two display-types: monoscopic large screen display (MD) (stereopsis was turned off) or stereoscopic large screen display (SD).

The within-subjects conditions are the gesture sets and gesture types. These conditions are further detailed in the following sections.

4.1 Gesture Sets and Types (Within-Subjects Conditions)

Participants were assigned to perform the task using two gesture sets:

- *Dynamic:* Refers to dynamic hand gestures based on hand motions and pointing gestures using hand or arm location. In this case, the user had to perform the gestures in the most open-ended way that they felt comfortable with and were asked to maintain consistency along all the trials.
- *Static or train gestures:* Refers to static hand gestures based on hand postures. In this case, the user learned how to perform the gestures and were asked to maintain consistency along all the trials.

To determine the types of gestures performed in each set and define how the users should execute them five investigators participated in a preliminary data collection session. They performed a selection task on lightweight physical objects to identify how users would interact with these objects using natural gestures they would use in the real world. These actions were tracked, recorded and analyzed to define the types of gestures and instructions for the static set. Based on the analysis we found that most of the gestures performed by users were:

- *Push:* Fully extend the arms in front of the body.
- *Pull:* Bring the hands inwards, towards the body.
- *Divide:* Separate the hands sideways.
- *Hold:* Extend the arms to hold and object in the air.
- *Volume Selection:* Define an arbitrary shape of an object to select it.

Each user performed the gestures in 5 sets of trials in both a dynamic and a static manner. Each set of trials was performed in a random order, which is given in Table 1.

4.2 Apparatus

We used OptiTrack Tracking Tools (OTT) [13] to capture 6-degrees of freedom (6DoF) position and orientation values of wrist, elbow and shoulder joints. Hand joint movement values collected from OTT were recorded using the modified NatNet SDK. We also used CyberGlove II [14] to record the angles of the bending of finger joints. In order to record the position and orientation of the forearm in space we attached infrared trackers to the wristband of the CyberGlove. Additionally, VRUI [15] was used to create a 3D visualization that was displayed to the participants. However, there was no visual feedback to their actions. This was done in order to motivate the users to perform actions freely and without any application specific restrictions or cause/effect of their interactions.

Table 1. Random order of tasks for a trial

Type of gestures					
Order 1	Push	Pull	Divide	Hold	Volume selection
Order 2	Pull	Hold	Volume selection	Divide	Push
Order 3	Volume Selection	Divide	Push	Pull	Hold
Order 4	Divide	Push	Volume selection	Hold	Pull
Order 5	Hold	Pull	Divide	Push	Volume selection

4.3 Programming Approach

For this research, the NatNetClient [16] was used collaboratively with the VirtualHand SDK [17]. A C++ program was created to collect position and orientation values from NatNetClient. It also creates virtual hands to display the user's movement using the values received through the CyberGlove. The positional values from OptiTrack were also saved in a separate .dat file for data analysis.

4.4 Data Collection

For calculating CRP values we classified the direction of movement occurred during a gesture according to body planes. Human movements are described in 3D based on a series of planes and axes. There are three planes of motion called body planes that pass through the human body: sagittal plane, frontal plane and transverse (horizontal) plane (Fig. 1a). A body joint movement occurs in all three planes, however, when describing the dominant plane movement, it is classified in just one of the three planes, the one where most movement occurs [18]. For any gesture, we analyzed the dominant plane by plotting the average distance over all trials for each participant. Each gesture was represented by its dominant plane, which also was used for computing the CRP values.

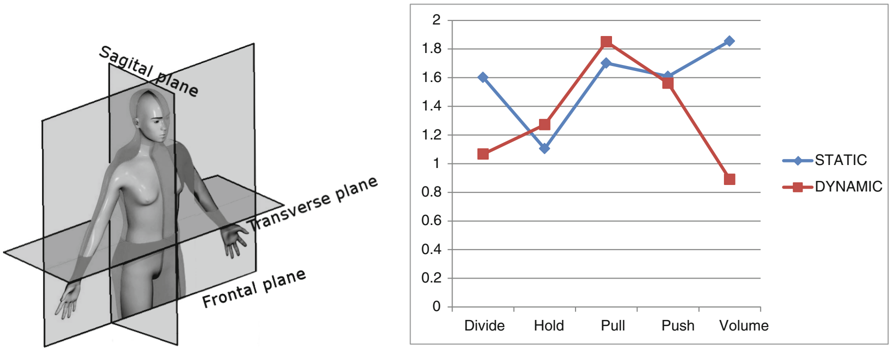


Fig. 1. (a) Body planes [19] and (b) Phase by Gesture Set

Phase angles were calculated using Eq. 2, where position and velocity were computed based on the dominant axis for left hand and right hand joints during the entire movement cycle. Movement values were calculated in an experimental setup where participants' data were different in terms of movement range. The data values were normalized across all trials to minimize all the influence of different movement amplitudes. CRP values were calculated at each frame and then normalized so that 0 % specifies the beginning and 100 % specifies the end of the gesture movement. Using this new range CRP values were aligned and then averaged.

4.5 Participants

A total of 20 participants (10 females, 10 males, mean age = 25.05 and SD = 3.28) participated in the study, either using a stereoscopic display (N = 10) or a monoscopic display (N = 10). All of them were right handed. Before participation, all of them completed a range of motion assessment without any difficulty.

4.6 CRP Results

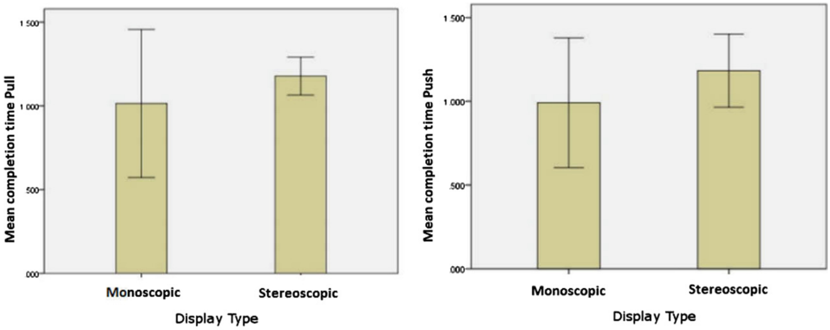
We determined the average variability of CRP values for different experimental conditions. The higher the variability the higher the coordination between hand movements. This gave insight on how well hand movements were coordinated as in-phase or out-of-phase and whether the movements were randomly shifting causing more muscle usage. The coordinated movements for in-phase and out-of-phase range by gesture set are plotted in Fig. 1b.

4.7 NASA-TLX Overall Workload

TLX overall workload, TLX temporal and TLX effort measures were independently averaged for each participant across testing sessions. A one-way ANOVA on NASA-TLX showed there were no significant differences between participants that were grouped by gesture type. An ANOVA testing for TLX overall workload showed a main effect of display type F(1, 18) = 11.81, p = 0.003, whereas p using stereoscopic display reported higher overall workload (mean = 39.73, SD = 3.32). A one-way ANOVA found there is a significant difference among display types for TLX temporal demand F (1, 18) = 6.08, p = 0.24 (whereas p using stereoscopic display showed higher temporal demand, mean = 42, SD = 12.07) and for TLX effort demand F(1, 18) = 6.545, p = 0.20 (whereas p using stereoscopic display reported higher effort demand, mean = 44, SD = 5.16).

4.8 Completion Time Results

Mean completion times showed a main effect of display type on pull gesture F(1, 2) = 20.782, p = .045 (whereas p using stereoscopic display showed higher completion time, mean = 1.18, SD = .13) and on push gesture F(1, 2) = 29.886, p = .032 (whereas p using stereoscopic display showed higher completion time, mean = 1.18, SD = .24) (Fig. 2). These values were computed within each of the experimental conditions and averaged over all trials for each participant. One-way ANOVA showed there was no significant differences in mean completion times for the participants that were grouped by order of gesture type, with each F<1.



(a) Avg. Completion time for Pull

(b) Avg. Completion time for Push

Fig. 2. Average completion time by display types

4.9 Users Perceptions

After the exercise a qualitative open-ended questionnaire was given to each participant to debrief and interview them about fatigue, task completion satisfaction, preference of one-hand vs two-hand gestures and system predicting the gestures and other issues. The mean results of responses are summarized in Table 2.

Table 2. Post-questionnaire responses

	Mean	SD	Liker scale
Task was easy	6.35	0.933	1 = Very difficult 7 = Very easy
Feelings of tiredness in arms at the end	5.6	1.40	1 = Very tired 7 = Normal and relaxed
Feelings about own performance	5.9	1.12	1 = Very unsatisfied 7 = Very satisfied
Perception towards gesture performance	6.1	0.97	1 = Very unsatisfied 7 = Very satisfied
Suitability of gestures	5.75	0.91	1 = Not suited at all 7 = Very suitable

5 Discussion and Design Guidelines

In this section we discuss our interpretation of the results and produce guidelines for design of interaction techniques to reduce fatigue in bimanual gesture-based interaction.

For NASA-TLX overload, the Stereoscopic Display (SD) condition showed significantly higher overall workload, temporal demand and effort demand than for Monoscopic Display (MD) condition. The order of the nature of the gestures performed did not affect the choice of gestures created by participants for the open-ended trials. Further investigation would be required to determine the true source of what causes effort demand in gesture performance.

The range of CRP values for all relationships and periods of stance was between $-45°$ and $45°$ for the experimental condition of SD. In this case, all the gestures were performed with anti-phase movement with CRP values in between $-90°$ and $90°$. The higher median standard deviation for CRP values was observed in the SD condition compared to the MD condition. This shows that participants who performed in the SD condition showed higher variation in maintaining the coordination pattern across all trials.

In the SD condition subjective measures showed significant values for overall workload, temporal demand and effort demand. This suggests that higher workload requirement can likely cause fatigue. With CRP analysis higher variability in coordination pattern was visible in the SD condition, which suggests that frequent change in coordination patterns can likely induce fatigue. However, higher variability in CRP values can also suggest inter-trial and inter-person inconsistent performance throughout the trials. More specific gestures to perform the task can be implemented in the future to test the validity of CRP variation.

For user comfort feelings of tiredness were found to be not statistically significant, however, from follow-up interviews it was revealed that discomfort may have been caused because of the wearing of gloves. In the SD condition, both pre-defined and open-ended gestures showed higher variability during volume selection gesture throughout the movement cycle.

6 Conclusion

Statistical analysis showed that when there was significant effect of stereoscopic displays on total workload, temporal and effort demand, CRP values also showed higher variability during the display condition. There was no significant effect of nature of gesture and order of display type chosen for a trial.

Our results show that CRP analysis can be a cheaper alternative to objective clinical measures like EMG to analyze level of fatigue. CRP variability can report fatigue-causing factors with precision and as a measurable quantity. By using the understanding of fatigue as a measurable factor, hand gestures can be designed. We expect that this study will aid in the understanding of human motor coordination and provide more detailed information on attributing causes, leading to design guidelines for future gesture-based interaction.

6.1 Future Work

Further studies on our research work can be done to improve the quality of results produced in this research. We think that some of the areas that need more research to understand hand coordination and fatigue are: (a) Compare with other standard subjective measures to verify the results from our study, and (b) Create gesture designs using our fatigue reporting method and validate the user experience feedback with CRP variability.

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