The Consumed Endurance Workbench: A Tool to Assess Arm Fatigue during Mid-Air Interactions

Juan David Hincapié-Ramos
University of Manitoba
Winnipeg, MB, Canada
hincapjd@cc.umanitoba.ca

Xiang Guo
University of Manitoba
Winnipeg, MB, Canada
umguo62@cc.umanitoba.ca

Pourang Irani
University of Manitoba
Winnipeg, MB, Canada
irani@cc.umanitoba.ca

Abstract

Consumed Endurance (CE) [8] is a metric that captures the degree of arm fatigue during mid-air interactions. Research has shown that CE can assist with the design of new and minimally fatiguing gestural interfaces. We introduce the Consumed Endurance Workbench, an open source application that calculates CE in real time using an off-the-shelf skeleton tracking system. The CE Workbench tracks a person's arm as it is moved in mid-air, determining the forces involved and calculating CE over the length of the interaction. Our demonstration focuses on how to use the CE Workbench to evaluate alternative mid-air gesture designs, how to integrate the CE Workbench with existing applications, and how to prepare the CE data for statistical analysis. We also demonstrate a mid-air text-entry layout, SEATO, which we created taking CE as the main design factor.

DIS '14, Jun 21-25 2014, Vancouver, BC, Canada
ACM 978-1-4503-2903-3/14/06.
http://dx.doi.org/10.1145/2598784.2602795

Author Keywords

Gorilla-arm, arm fatigue, mid-air interactions, mid-air gestures, endurance, consumed endurance

ACM Classification Keywords

H.5.2. Information interfaces and presentation (e.g., HCI): Evaluation/Methodology.

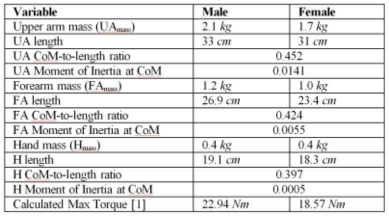
Introduction

Mid-air gestural interfaces are now used in a variety of settings including classrooms [4], video games [9], and even sterile medical rooms [2][10]. Despite the naturalness and benefits of mid-air interfaces, users often report arm fatigue as major usability obstacle - a condition known as the gorilla-arm effect. To support prolonged user engagement through mid-air interfaces, system designers should minimize the amount of arm fatigue that results from interacting with their systems.

Existing approaches to assess arm fatigue include obtrusive measurements of bodily variables (heart-rate [13], oxygen level [5] or EMG [11]) or the collection of subjective assessments (Borg [3], NASA-TLX [7] or Likert ratings). These methods have limited practical value for designing mid-air interactions as they require specialized equipment or have high variance. A recently proposed metric, Consumed Endurance (CE), allows system designers to measure fatigue without obtrusive body instrumentation [8]. CE is calculated as the ratio between the interaction time and the average endurance time associated with the user's arm movements. CE has been validated against the popular Borg CR10 scale with very strong to perfect association.

We demonstrate the CE Workbench, an open source application created to facilitate the capture and analysis of Consumed Endurance. The CE workbench can help designers capture arm fatigue from gestural interfaces for different purposes. Designers of everyday applications may seek to minimize arm fatigue, while physiotherapists and exergame designers may have interest in gradually increasing arm effort. We demonstrate how CE can be applied to create new designs, such as the SEATO keyboard layout aimed at minimizing arm fatigue in mid-air text-entry. Our demonstration focuses on:

- How to use the CE workbench as a tool for evaluating alternative mid-air gestures?
- How to statistically analyze and report CE data?
- How to extend, integrate and collect CE using our workbench with custom applications?



Variable	**Male**	**Female**
Upper arm mass (UA_{mass})	2.1 *kg*	1.7 *kg*
UA length	33 *cm*	31 *cm*
UA CoM-to-length ratio	0.452	
UA Moment of Inertia at CoM	0.0141	
Forearm mass (FA_{mass})	1.2 *kg*	1.0 *kg*
FA length	26.9 *cm*	23.4 *cm*
FA CoM-to-length ratio	0.424	
FA Moment of Inertia at CoM	0.0055	
Hand mass (H_{mass})	0.4 *kg*	0.4 *kg*
H length	19.1 *cm*	18.3 *cm*
H CoM-to-length ratio	0.397	
H Moment of Inertia at CoM	0.0005	
Calculated Max Torque [1]	22.94 *Nm*	18.57 *Nm*

Figure 1: Arm weight, length, inertia, center of mass, and max forces for the 50th percentile female and male.

Calculating Consumed Endurance (CE)

Hincapié-Ramos et al. present a detailed description of how to calculate CE [8]. Equation 1 presents CE as the ratio between the interaction time (*IntTime*) and the available endurance time (*E(Torque)*).

$$CE(Torque, IntTime) = \frac{IntTime}{E(Torque)} * 100 \qquad (1)$$

Endurance time – the maximum amount of time that a muscle can maintain a contraction level before needing rest [12] – is a function of the average torque at the shoulder joint required to move the arm for performing a particular mid-air gesture (see Equation 2).

$$E(T_{shoulder}) = \frac{1236.5}{\left(\frac{T_{shoulder}}{T_{max}} * 100 - 15\right)^{0.618}} - 72.5 \qquad (2)$$

We solve these equations with an off-the-shelf skeleton tracking system to determine the arm position, and biometric constants for the arm length, weight and maximum forces at the 50th percentile [6] (Figure 1).

The CE Workbench Software Platform

Figure 2 shows the CE Workbench interface, an open source application that calculates CE using skeleton data as provided by a Microsoft Kinect camera[1]. The CE workbench computes CE for a single user standing in front of the camera. The left side of Figure 2 shows the camera view and the overlapping skeleton. The red circle represents the current strength at the associated shoulder joint (100% of strength equals 50px radius).

The right side of Figure 2 shows one ongoing capture of CE, and two previous ones stacked right below. For

---

[1] CE Workbench is a Microsoft C#/WPF application. Platform independent C++ libraries where CE is computed are available.

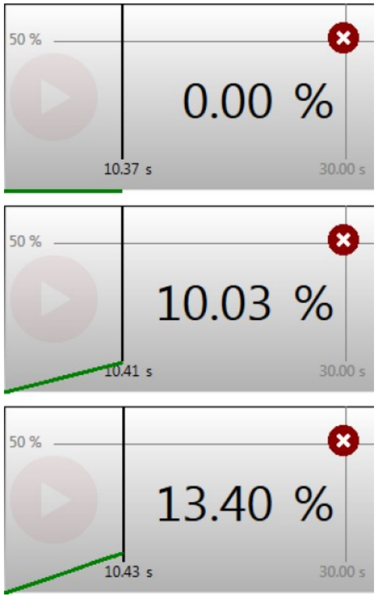


Figure 3: Sample CE captures holding the arm at fixed angles for ~10 sec. Top: At rest, strength is below 15% and thus CE is 0%.
Middle: At ~45°, CE is 10.03%.
Bottom: At ~100°, CE is 13.40%.

each capture the system reports the final CE (big and bold number), its increase over time (trend line), and the total interaction time (vertical bar). Users can query CE at a particular point in time by moving the cursor on top of the trend line. Users can also replay a previously captured interaction to see the particular arm movements which lead to increases of CE.

The CE workbench presents the most frequent controls on the lower-right corner, and the least used settings can be accessed from the top-right button. Users can start and stop the computation of CE manually, or let the system start automatically. From equation 2 we know that below a strength level of 15% endurance time is infinity. Therefore, when the automatic mode is enabled, the CE workbench starts computing CE when strength is above the 15% mark, and stops when it's below. The "Export" button allows users to export the captured CE values as a comma-separated values (CSV) file for statistical analysis on external tools. On the settings dialog, users can specify whether to calculate CE for the left or right arm, the gender specific variables, and the target folder for saving the skeleton recording files.

Users of the CE workbench (and visitors to our demo) can interact with the software by performing several mid-air gestures in front of the camera, as well as using the software to analyze the captured CE data.

Statistical Analysis of CE

CE is a scalar value and therefore can be analyzed with traditional statistical tools such as t-tests and analysis of variance (ANOVA). However, we have encountered situations where CE does not comply with the normality and sphericity conditions of such tests. In such cases designers can use the ART ANOVA for non-parametric data [14][8].

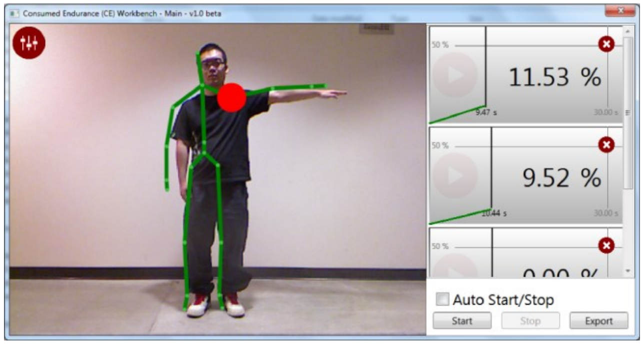


Figure 2: CE Workbench in action. The line-charts on the right present the evolution of CE over time. Automatic capture starts/stops when crossing the 15% arm strenght threshold.

Extending/Integrating the CE Workbench

CE workbench can be integrated with custom software in three ways: *embedded*, *inter-process*, *internal*. Designers can embed their custom code within the CE workbench itself by inheriting from the *IApplication* interface and registering the new application object at startup. For example, a new gesture recognizer can be integrated in the CE workbench as an application object. Application objects receive notifications of new Kinect streams and skeleton data in a way similar to other SDKs. Another alternative is to use the CE workbench's OSC-based protocol to send skeleton data from a standalone application. Finally, designers can use the CE C++ libraries and C# wrapper to import them into their own applications. The CE workbench includes examples of how to use CE from different languages and with data from different skeleton tracking systems.

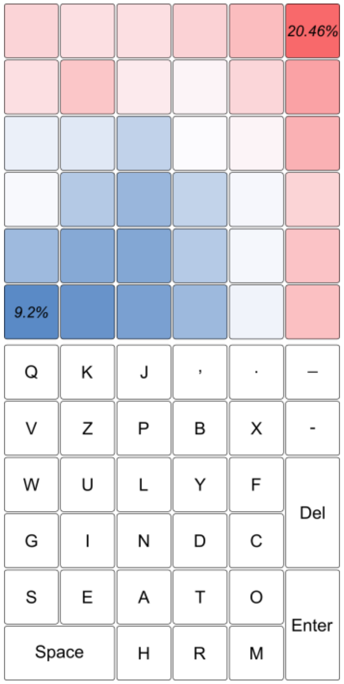


Figure 4: Top- Heatmap of strength for a virtual grid in front of the user. Bottom- The SEATO layout, an endurance-efficient keyboard for mid-air interfaces.

SEATO: A Sample CE-efficient Keyboard

CE can aid in the design of novel mid-air interfaces. We demonstrate how CE guided the design of an endurance-efficient text entry layout. Mid-air text entry normally uses the QWERTY layout or an ordered ABC sequence for in an attempt to leverage the users' existing knowledge. However, such layouts were designed for other situations. We used strength, an associated CE metric (calculated as T/Tmax in equation 2), to create a heatmap of the cells in a virtual grid in front of the user which require the most effort to reach. We then organized the alphabet characters according to their frequency in the English language (see Figure 4). We located the most frequent characters in the cells requiring the least strength. Experimental results [8] confirmed that SEATO requires less CE than QWERTY, and thus SEATO entails less arm fatigue.

Downloading the CE Workbench

Get the CE library files and sample applications at: https://github.com/hcilab-um/ArmFatigueCE. We welcome feedback and suggestions for improvement.

References

[1] Tan, H., Radcliffe, J., Ga, B.N., Tan, H.Z., Eberman, B., Srinivasan, M.A., and Cheng, B. 1994. Human factors for the design of force-reflecting haptic interfaces. Dynamic Systems and Control, 55, 353-359.

[2] Bigdelou, A., Schwarz, L., and Navab, N. 2012. An adaptive solution for intra-operative gesture-based human-machine interaction. In Proc. IUI '12, ACM.

[3] Borg, G. 1998. Borg's Perceived Exertion and Pain Scales. Human Kinetics.

[4] Cuccurullo, S., Francese, R., Murad, S., Passero, I., and Tucci, M. 2012. A gestural approach to presentation exploiting motion capture metaphors. In Proc. AVI '12, ACM.

[5] Ferguson, S.A., W. Gary, A., Le, P., Rose, J.D. and Marras, W.S. 2011. Shoulder Muscle Oxygenation During Repetitive Tasks. Human Factors and Ergonomics Society Annual Meeting 55,1, 1039-1041.

[6] Freivalds, A. 2004. Biomechanics of the Upper Limbs: Mechanics, Modeling, and Musculoskeletal Injuries. 1 ED. CRC Press.

[7] Hart, S.G., and Stavenland, L.E. 1998. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. Human Mental Workload, P. A. Hancock and N. Meshkati, Eds.

[8] Hincapié-Ramos, J.D., Guo, X., Moghadasian, P. and Irani. P. 2014. Consumed Endurance: A Metric to Quantify Arm Fatigue of Mid-Air Interactions. In Proc. CHI '14, ACM, Toronto, Canada. *To Appear.*

[9] Huang, M.-C., Chen, E., Xu, W., and Sarrafzadeh, M. 2011. Gaming for upper extremities rehabilitation. In Proc. WH '11, ACM.

[10] Mentis, H. M., O'Hara, K., Sellen, A., and Trivedi, R. 2012. Interaction proxemics and image use in neurosurgery. In Proc. CHI '12, ACM.

[11] Peres, S.C., Nguyen, V., Kortum, P.T., Akladios, M., Wood, S.B., and Muddimer, A. 2009. Software ergonomics: relating subjective and objective measures. In CHI EA '09, ACM.

[12] Rohmert, W. 1960. Ermittlung von erholungspausen fr statische arbeit des menschen. European Journal of Applied Physiology and Occupational Physiology 18. 123–164.

[13] Sjgaard, G., Savard, G., and Juel, C. 1988. Muscle blood flow during isometric activity and its relation to muscle fatigue. European Journal of Applied Physiology and Occupational Physiology 57, 327–335.

[14] Wobbrock, J.O., Findlater, L., Gergle, D., and Higgins, J.J.. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In Proc. CHI '11. ACM.