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Modeling people with motor disabilities to empower the automatic accessibility and ergonomic assessment of new products

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A B S T R A C T

Virtual User Models (VUMs) can be a valuable tool for accessibility and ergonomic evaluation of designs in simulation environments. As increasing the accessibility of a design is usually translated into additional costs and increased development time, the need for specifying the percentage of population for which the design will be accessible is crucial. This paper addresses the development of VUMs representing specific groups of people with disabilities. In order to create such VUMs, we need to know the functional limitations, i.e. disability parameters, caused by each disability and their variability over the population. Measurements were obtained from 90 subjects with motor disabilities and were analyzed using both parametric and nonparametric regression methods as well as a proposed hybrid regression method able to handle small sample sizes. Validation results showed that in most cases the proposed regression analysis can produce valid estimations on the variability of each disability parameter.

1. Introduction

It is important to realize that people with disabilities are not a tiny minority of the population. Around 640 million people worldwide live with a disability (Enable, 2008). Many strategies have been undertaken worldwide to enforce accessibility for people with disabilities. For instance, the European Commission has launched a number of initiatives (Klironomos et al., 2006; Bühler and Stephanidis, 2004), such as the eEurope 2002, the eEurope 2005, the EDeAN network and the DfA@eInclusion Coordination Action (Šimšík and Galajdová, 2008) to promote the "Design For All" (DfA) principles that will lead to more accessible services and systems. The Commission has also advocated the use of standardization to improve the effectiveness and uptake of DfA. It mandated CEN, CENELEC and ETSI to include the "Design for All" concept in relevant standardization initiatives. Digital Human Modeling (DHM) can significantly support designers and developers on staying compliant with the aforementioned strategies, as it reduces the need for physical prototypes, and also enables the incorporation of ergonomics science and human factors engineering principles earlier in the design process.

DHM and simulation has gained importance in the past few years (Phillips and Badler, 1988; van der Meulen and Seidl, 2007; Porter et al., 2004; Lind et al., 2008; Feyen et al., 2000) and allows designers to easily observe and evaluate the interaction of the designed product with a virtual user having specific needs and/or preferences. Simulation offers designers the opportunity to explore how a new system would behave before the real prototype is developed, or how an existing system would perform if altered, thus, reducing development time and costs. Moreover, there are cases where simulation is the only method of verifying that a design concept is acceptable to a prescribed population, since hardware prototypes are not available (Chaffin, 2001).

The core concept of this paper is to empower the accessibility and ergonomics of new products by introducing a novel user modeling technique for people with disabilities, based on statistical analysis. The main goal of the paper is the development of accurate Virtual User Models (VUMs) representing specific disabled population groups. Measurements were initially obtained from a total of 90 subjects having the following disabilities: Parkinson's disease, stroke, multiple sclerosis and cerebral palsy. Statistical analysis was performed on these measurements using both parametric and nonparametric regression analysis, as well as a proposed hybrid regression method able to handle small sample sizes by using both real and virtual samples along with information found in the literature. The accuracy and validity of the final regression results

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were assessed using a new set of measurements coming from 72 different subjects with the same four disabilities.

1.1. Previous work

In recent years, the advent of new tools for musculoskeletal simulation has increased the potential for significantly improving the ergonomic design process and ergonomic assessment of designs (Rasmussen et al., 2012). Garg and Kapellusch (2009) summarized the possibility of 2D and 3D biomechanical models for the prevention of work-related musculoskeletal disorders. Musculoskeletal models consist of a set of body segments connected by joints with specified degrees-of-freedom (dof) and spanned by muscles and ligaments with specified origins, insertions and pathways (Damsgaard et al., 2006). Indicative is the work of Lee et al. (2009) that introduced a highly-detailed biomechanical model of the human upper body. Its dynamic skeleton comprises 68 bones with 147 jointed degrees of freedom while its muscle model incorporates 814 muscles, each of which is modeled as a piecewise uniaxial Hill-type force actuator. Other significant efforts on biomechanical modeling can be found in (Sifakis et al., 2005; Lee and Terzopoulos, 2006; Sueda et al., 2008; Sartori et al., 2013; Pontonnier et al., 2014).

Inverse kinematics plays a key role in the simulation of articulated figures for accessibility assessment purposes and ergonomics. Often these figures contain more than a hundred degrees of freedom, making it almost infeasible for the animator to manipulate every joint to control the figure's posture. With the assistance of an inverse kinematics algorithm, the animator merely gives the desired location of certain chosen points on the body and relies on the algorithm to automatically compute a set of joint angles that satisfy the end-effector constraints (Tolani et al., 2000). Likewise, inverse-dynamics (Kuo, 1998; Blajer et al., 2007) plays also a key role in accessibility assessment of virtual prototypes through simulation, as it enables the computing of the internal joint forces and moments associated with a measured motion (Wagner et al., 2007). Inverse dynamics computes the muscle activation based on a specific task and, although this puts many restrictions on the model, it is computationally much more efficient than forward dynamics (Damsgaard et al., 2006).

Special populations of individuals, including people with disabilities and older people, may have capabilities that are quite different even from what is published in some ergonomics guides for people with functional limitations (Chaffin, 2005). Thus, there is an imperative need for research on the development of predictive and valid models providing accurate results regarding the functional limitations of people with disabilities. The two main approaches employed in statistical user modeling are *content-based* and *collaborative* (Zukerman and Albrecht, 2001). In the *content-based* approach, the behaviour of a user is predicted from his or her past behaviour, while in the *collaborative* approach, a user's behaviour is predicted from the behaviour of other “similar” people. When trying to identify how functional limitations vary over a population having a specific disability, in order to develop accurate VUMs representing people with disabilities, the *collaborative* approach seems most suitable.

Statistical analysis can lead to realistic assumptions about the users' functional limitations and can be a powerful tool for the identification of possible associations between disability parameters. For instance, linear regression modeling revealed that demographic and stroke pathology factors like age, sex, premorbid disability, side of stroke and stroke type as well as visuospatial neglect are not associated with balance disability after stroke, while weakness and sensation are strongly related with balance disability (Tyson et al., 2006). Langenderfer et al. (2006) tried to simulate variability in musculoskeletal parameters on glenohumeral external rotation strength in healthy normals, and in rotator cuff tear cases using a Monte Carlo model. The goal was to determine if variability in musculoskeletal parameters could quantifiably explain variability in glenohumeral external rotation strength. The model predicted measured joint torques for healthy normals, subjects with supraspinatus tears, and subjects with infraspinatus–supraspinatus tears with small error.

Moreover, regression models may also lead to forecasts about a person's health state. Khaleeli et al. (2008) used ordinal logistic regression to predict progression in primary progressive multiple sclerosis. Regression analysis identified the following independent variables that predicted progression: male sex, shorter disease duration, slower timed walk at baseline (best overall predictor), deterioration in expanded disability status scale score and reduction in brain volume over 2 years. Vaneckova et al. (2012) used non-parametric and multiple regression models to identify the most reliable predictors of multiple sclerosis and its changes over 9 years. The results of the study revealed corpus callosum atrophy as an accurate predictor of future disability accumulation. Multivariate parametric regression models have also been developed to predict short-term disability in multiple sclerosis (MP) patients using the Expander Disability Status Scale (EDSS) and multimodal sensory EP (mEP) to optimize decisions concerning treatment (Margaritella et al., 2012).

Some research efforts focused on the variability in the capability of an individual based on the disability severity. For instance, Carpinella et al. (2007) examined the quantitative description of locomotor symptoms in subjects with mild Parkinson's Disease and results showed a tendency to bradykinetic gait, with reduction of walking speed and cadence. Steultjens et al. (2000) assessed the relationship between joint range of motion (ROM) and disability in patients with osteoarthritis of the hip or knee and even the results showed a clear relationship between joint ROM and disability, it does not apply to all actions of the knee or hip joints. Various scales have been proposed to describe the severity of each disability and be used for functional outcome prediction. In general, such a scale consists of several variables for observing the signs and symptoms, and each variable is categorized for scoring. For instance, the Stroke Impairment Assessment Set (SIAS) (Chino et al., 1996) rates performance on scales of 0–5 or 0–3. SIAS total scores proved useful for stroke outcome prediction (Tsuji et al., 2000). However, a typical limitation of severity scales is that scores can be translated into a range of values, not a single value. In SIAS, for instance, when passive shoulder abduction is limited to less than 45°, a score of 0 is given. A score of 1 means that the joint can be abducted from 45° to 90°, a score of 2 indicates abduction from 90° to 150°, and a score of 3 indicates that abduction of the shoulder beyond 150° is possible.

Many efforts have been presented regarding the simulated accessibility assessment of designs using virtual humans. An indicative case is the HADRIAN tool (Marshall et al., 2010), which uses virtual user representations based on measurements of physical characteristics and capabilities of 100 real individuals (Gyi et al., 2004). However, HADRIAN uses these 100 virtual humans as personas and performs accessibility assessment for each of these virtual personas independently. A design may be found accessible or inaccessible for a specific persona. But as this persona represents a single real person and not a population group, the assessment result cannot be generalized, in order to consider the specific design as generally accessible or inaccessible.

1.2. Motivation and contribution of the paper

As increasing the accessibility of a design is usually translated into additional costs and increased development time, due to