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Modeling movements of a long hand-held tool with effects of moments of inertia

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ABSTRACT

The current experiment aimed to investigate the effects of weight position on movement time in target acquisition tasks. Subsequently, a simple mathematical model was developed to describe the movement time with the moments of inertia. Ten right-handed participants conducted continuous Fitts pointing tasks using a laparoscopic instrument as a long hand-held tool. The results showed significant effects of weight position on movement time. Furthermore, an extended Fitts' law model is proposed for the moments of inertia produced by the hand, instrument, and a constant mass in different positions. This predictive model accounted for 63% of the variance in movement time. The predictive model proposed in the present study can be applied not only to estimate movement time given a particular target width, instrument movement amplitude, and weight position of a long hand-held tool but also to standardize movement time and establish training standards.

1. Introduction

The aim of this study is to model the visually-controlled movements of a long hand-held tool including the effects of weight position. In particular, it represents an attempt to propose an alternative Fitts' law model where movement time (MT) is relative to moment of inertia produced by a constant mass in different weight positions.

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Investigations of industrial applications indicate that the length (Baird, Hoffmann, & Drury, 2002) of hand-held tools substantially affects movement time. A longer probe imparts effectively a higher gain to the hand-eye coordination system. Such an increase in gain can be expected to reduce the first component of movement time (the distance-covering phase), wherein the person moves the tool to the general vicinity of the target, but it may increase the movement time of the second component (the homing-in phase), wherein the target is finally acquired (Baird et al., 2002). However, numerous psychophysical studies (Turvey, 1996; Turvey & Carello, 1995) have determined that rather than mass, or even length, the physical quantity that accounts for nearly all variance in haptic perceptual tasks is the object's rotational inertia, or its resistance to rotation in three-dimensional space. This haptic perceptual performance is fairly robust as well during the simultaneous performance of both a perceptual task and a secondary rhythmic-aiming task (Santana, 2003). It is important for human factors specialists to understand the abilities and limits of haptic perceptual performance during dual- or multiple-task situations, but at the same time, in the industrial engineering field, it is important to predict the time of human motion as well. To sum up the results of previous studies, given that the length of a long hand-held tool remains constant, one would expect that the moments of inertia produced by a tiny mass located at different positions on the tool would affect motor performance during its manipulation. For this reason, the current study applied Fitts' law (Fitts, 1954) to investigate this likely phenomenon.

In a study of hand-held tools in visually-controlled movements by Fitts (1954), an experimental task was applied to quantify the accuracy and performance of the movement. In the Fitts paradigm, the index of difficulty was defined by the distance to the target and the size of the target. The relation between the index of difficulty and the movement time was assumed to be linear.

A typical task in the Fitts experiment is that a subject moves a pointed stylus as rapidly as possible between two fixed targets of width (W) set a distance (A) apart and hits the targets with the stylus. The movement time (MT) can be predicted by the following Eq. (1):

$$\mathrm{MT} = a + b\log_2\left(\frac{2A}{W}\right) \tag{1}$$

where a and b are empirical constants determined through linear regression. The *log* term is called the index of difficulty (ID) and carries the unit bits.

Some variations of the law have been proposed by direct analogy with Shannon's Theorem 17 (Shannon, 1948). MacKenzie (1989) developed an equation that differs only in the formulations for ID, as shown in Eq. (2). The benefits of this equation are that ID is never a negative value and that this equation provides a better fit with observations (i.e., a higher correlation-coefficient is typically achieved).

$$\mathrm{MT} = a + b\log_2\left(\frac{A}{W} + 1\right) \tag{2}$$

In order to investigate the effects of weight distribution produced by a constant mass on visually-controlled movement performance, Lin, Chen, and Lo (2011) conducted a Fitts task wherein participants used a laparoscopic instrument as a long hand-held tool to point at targets. Their results showed significant differences in performance according to the weight distribution. Unfortunately, they did not further investigate the relation between movement time and moments of inertia that were produced by the different weight distributions, nor did they develop a movement time predictive model.

As described above, the major structure of the long hand-held tool is a long probe. The efficiency of manipulating a long shaft tool has been studied extensively. Baird et al. (2002) discovered many examples in which the tool used for making a highly precise movement was not just a simple pencil or similar pointer, but rather an implement whose extreme length increased the difficulty of movement. Therefore, they investigated the effects of probe length on movement time based on Fitts' law. It should be noted that in their study, the mass moment of inertia about the grasp point varied slightly and was assumed to be negligible in comparison with that of the arm or hand. Based on this finding, the increased probe length deleteriously affected movement performance.