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Seated leg/foot ballistic and visually-controlled movements

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ABSTRACT

An experiment with 52 participants investigated the relationship between movement time of the leg/foot for seated persons when moving in the transverse and sagittal planes. Four amplitudes of movement and 11 values of Fitts' Index of Difficulty (ID) were used to determine conditions under which ballistic movements could be made along with the need for visual control at higher ID values. Vision of the foot was available in all movements. As with arm movements (Gan and Hoffmann, 1988) there was a critical ID value below which it was possible to use ballistic movements and where movement times were approximately linear with the square-root of movement amplitudes. Above these ID values, Fitts' law applied, with gradients dependent on the amplitude of movement, suggesting that the muscle torque applied to the leg varied with movement amplitude. The critical ID varied with the amplitude of movement as previously found for arm movements.

Relevance to industry: There is increasing use of the foot/leg for input to various controlling devices. Consequently it is necessary to have detailed information on the capacity of the leg/foot system to provide accurate input to a machine via a control pedal or other device. The present research provides such information over a wide range of control sizes and spacings.

1. Introduction

As foot controls are coming into more common use (Springer and Siebes, 1996; Van Veelen et al., 2003; Pannetier and Wang, 2014; Velloso et al., 2015), performance information is essential so that the control can be designed adequately for human operation. In order to achieve this, it is necessary to know in detail the value of Index of Difficulty (ID) at which there is a transition from where the person will make movements ballistically to movements where visual control may be used. Such data is partly available for conditions where vision of the moving leg/foot is not available (Hoffmann, 1991a) such as the movement from the accelerator to the brake pedal. However, when full vision of the limb is available during the movement, it is likely that movement times and the value of ID at which movements may be made without the use of the available visual feedback will be different to values when no vision of the moving leg/foot is available.

A review of the "What we know and what we do not know" about foot movements related to the use of foot movement controls was given by Ng and Chan (2009). Since that time, there have been a number of researches published on time for both ballistic (Park and Myung, 2012) and visually-controlled foot movement times (Chan et al., 2010; Chan and Hoffmann, 2015; Furtado De Mendonca Monco, 2015).

Other recent research, although not directly related to movement times, has investigated dynamic characteristics of the knee and elbow joints and provided valuable information for modelling leg and arm movements in terms of exponential rise times for movement, damping characteristics and natural frequency of limb movements. Passmore et al. (2015) have investigated movement times of legs with degenerative lumbar spinal stenosis to targets with ID ranging from 2 to 5 and amplitudes from 10 to 40 cm (6 conditions), in terms of kinematic characteristics such as peak velocity and time to peak velocity. Although it was stated that Fitts' law held for the data, a "larger than predicted influence of amplitude versus target width was observed" (page 282). Movements were made in the sagittal plane with the big toe used as a pointer to targets that varied in size from 2.5 to 5 cm. The authors did not take into consideration the effects of the toe size increasing the available target width when using a 'probe' of significant width (Drury, 1975; Hoffmann, 1995), so that the real ID values are likely to be less than those set in the experiment.

Park and Myung (2012) investigated the time taken for moving between pedals when a rotational foot movement was used. These

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authors found that, for rapid movements, the ballistic equation of Gan and Hoffmann (1988) gave an excellent description of their data. The most complete data on foot movement times is that of Chan and Hoffmann (2015). On the basis of data of Hoffmann (1991b) and Chan et al. (2010) they assumed that the critical ID for foot movement would be about the same as that for hand movements. The basis for this assumption, apart from the very limited experimental evidence that showed a levelling of movement time for ID < 3, was that the time for control loop closure must be about the same independent of the limb being used (assuming that there is vision of the moving limb). For their ballistic movements, Chan and Hoffmann (2015) used an ID value of 2.5 for the targets with varying amplitudes of movement, up to 600 mm. For studying movements with ongoing visual control, ID values of 4, 5, and 6 were used along with amplitudes of 200, 400, 600 mm.

An important feature of the data of Chan and Hoffmann (2015) was that, at an ID of 2.5, the standard form of the ballistic movement time equation in which MT is linear in the square-root of movement amplitude A (Hoffmann, 1981; Gan and Hoffmann, 1988) did not apply. It was expected that,

$$MT = c + d\sqrt{A} \tag{1}$$

In place of this relationship, the data showed better regression in terms of a model in which MT was linear in the amplitude of the movement,

$$MT = e + f\,A \tag{2}$$

This result was different to that of other experiments and may have been due to a number of reasons:

i. The critical ID value may be smaller for leg/foot movements than for hand/arm movements, so that some visual feedback may have been used in making the movements.
ii. Movement times of the foot were much longer than those for the hand and hence may have allowed some visual feedback control of the movement. That is, the movements may not have been carried out in a fully ballistic manner.
iii. The leg/foot system may not have as high a ratio of muscle strength to mass moment of inertia as the hand/arm system and hence may allow full visual control to lower values of ID.

It is noted that in the experiments of Hoffmann (1991a) for movements between an accelerator and brake pedal, where vision of the movement was not allowed, the movements were faster than in Chan and Hoffmann (2015) and also followed the ballistic movement time equation (2). In the research of Hoffmann (1991a), a review of the sizes and spacing of pedals associated with a foot movement from the accelerator to the brake showed a wide range of Index of Difficulty. These foot movements were made without visual control and hence are ballistic in nature. The mean value of ID for the sample of 42 motor vehicles surveyed was 2.4 without considering the effects of shoe width and approximately 0.7 when the effective target width was considered (Drury, 1975; Hoffmann, 1995; Hoffmann and Sheikh, 1991). As such controls are to be used without ongoing visual control, it is essential that they be designed so that the ID for foot operation is below the critical ID value. However, when visual control is available as in some foot operations, movements may be made to lower values of ID than those available without visual control. This may arise from the time available for making corrections due to the relatively low ratio of muscle strength to mass moment of inertia of the leg/foot compared to that of the hand/arm.

Detailed data for arm/hand movements are available (Gan and Hoffmann, 1988) which showed that there is a transition from the ability to use rapid, pre-programmed ballistic movements at low values of Fitts' ID (Fitts, 1954; Fitts and Peterson, 1964) to movements times that follow Fitts' law when the ID values are higher, typically greater than about three or four. Movement times (MT) are given by,

$$MT = a + b(ID) \text{ where the Index of Difficulty, } ID = \log_2(2A/W) \tag{3}$$

and A is the amplitude of the movement, W is the target width.

In the ballistic region of movement, times for arm movements are given by (Gan and Hoffmann, 1988),

$$MT = c + d\sqrt{A} \tag{4}$$

The transition or 'critical' ID value was found to be dependent also on the amplitude of the movement, so that a critical ID was given approximately by,

$$ID_{critical} = 2.58 + .101\sqrt{A}, \text{ with amplitude in mm.} \tag{5}$$

A review of critical index of difficulty for different body motions by Hoffmann (2016) showed that the various body components have different values of critical ID. It was suggested that the physical characteristics of the moved limb, such as mass and mass moment of inertia, along with the muscle strengths are determinants of the critical ID. As the ratio of these two quantities increases, so the time available for making visual corrections increases and consequentially the critical ID value decreases. Only for a few body components were there sufficient data available for a reasonably accurate evaluation of the transition from ballistic movements to visually-controlled movements. Although it was possible to obtain approximate estimates of the critical ID for leg/foot movements, the available data did not allow accurate values to be established.

Thus the aim of this work was to determine the movement time relationship with changes of target ID and movement amplitude, in an experiment similar to that of Gan and Hoffmann (1988) for arm/hand movements.

2. Method

2.1. Participants

A total of 52 participants (26 males, 26 females) took part in the experiment, all with informed consent and under the ethical guidelines of City University of Hong Kong. Their ages ranged from 14 to 27 (Mean = 21.2, SD = 1.9 years). All were in good physical health.

2.2. Apparatus

A set of target boards with copper plates of the appropriate width were attached to a wood base plate. On each board, there was a starting plate, being the location where each movement was commenced. As well, each board had a target plate. During each task, only one of these target boards was visible to the participant. The target boards were electrically connected to an electronic timer recording in milliseconds. Participants were seated comfortably and the target boards were placed directly in front on the floor. A sharp-pointed metal probe attached to the shoe, and extending 40 mm in the front of the shoe, was used as the experimental probe. The timer started when the probe left the start plate and stopped when the target was hit. The targets had a height of 150 mm perpendicular to the direction of movement. Target widths (W)