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Constitutive kinematic modes and shapes during vehicle ingress/egress

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ABSTRACT

A study was undertaken to investigate the kinematics of older users of passenger vehicles during ingress/egress and to seek correlations between their movement and comfort rating assigned by the subjects to the ease of vehicle ingress and egress. A principal component analysis was performed on the subjects' kinematics to identify the underlying modes of movement employed by the subjects. It was found that a small number of modes could describe the movements of all the subjects across all of the vehicles. Within the subspace defined by the modal vectors, shapes were found which correlated to the comfort rating for ease of ingress and egress which the subjects had assigned to each of the cars. Knowledge of these shapes which correspond to good and poor ingress and egress will be useful to the designers of interiors and exteriors of passenger vehicles for the older person. It is recommended that vehicle designs for the older person should attempt to avoid body positions which require excessive ankle articulation and lumbar flexion/extension during ingress and egress.

1. Introduction

Comfort is a subjective concept which is difficult to objectively define and measure as there is no universally accepted operational definition of comfort (Leuder, 1983). Many researchers have adopted the definition of comfort as being "the absence of discomfort" (Hertzberg, 1972) as it is more straightforward to quantify discomfort than to measure comfort. Comfort and discomfort can best be understood under a theory of complexity since it emerges from a chain of interaction processes between the human and several elements of a system (Da Silva et al., 2012). The perception of comfort and discomfort is a multifactorial sensation which is a function of numerous factors mutually interacting and interacting with the subject in a complex manner.

In recent years, car manufacturers have increased their interest in vehicle comfort in general and ease of ingress/egress (I/E) in particular. To study ease of use, automobile manufacturers have sought validation using physical mock-ups of vehicles and subjective judgements given by subjects to correlate with vehicle dimensions (Tessier, 2000).

However with a growing ageing population and an increased number of people maintaining an active lifestyle well into their 80s, it is suggested that the design of vehicles would benefit from a clear understanding of the limitations related to age-associated reductions in physical mobility (Berman et al., 1988). According to Smith and Sethi (1975), joint flexibility declines by approximately 25% in older adults. These age-related restrictions occur naturally within an ageing musculoskeletal system, for example joint range of motion decreases with age and reduction in joint flexibility can lead to less efficient movement patterns (Daley and Spinks, 2000; Vandervoort, 2002).

Sarcopenia also occurs with the ageing process and specifically refers to loss of skeletal muscle mass. All men and women experience some degree of sarcopenia (defined as losses greater than 2 SD below the mean for young healthy controls) (Doherty, 2003); with prevalence ranging from 13 to 24% in persons aged 65–70 years; and over 50% for those older than 80 years (Baumgartner et al., 1998).

Rising from any chair is a biomechanically demanding task for the older person which requires co-ordination, balance, adequate mobility and strength (Riley et al 1991, 1997; Ikeda et al., 1991). Research suggests a range of biomechanical factors affect the ability

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to rise from a seat such as knee torque, horizontal and vertical linear momentum, balance, choice of seat rise strategy and upper and lower extremity strength (Hughes et al., 1994; Janssen et al., 2002) and older adults have been found to increase hip flexion and optimise knee joint velocities whilst rising from a chair (Schenkman et al., 1990; Hughes and Schenkman, 1996).

These difficulties are exacerbated during ingress/egress of a vehicle for an older person (Robert et al., 2014). A complete description of the joint loads occurring during I/E motions is not currently available (Robert et al., 2014). Few studies have reported on the I/E movement (Menceur et al., 2008) although existing studies of I/E movement have focussed on healthy able-bodied people (Giacomin and Quattrocolo, 1997; Lestrelin and Trasbot, 2005; Lempereur et al., 2005).

However, vehicle accessibility and meeting physical limitations related to age is a key vehicle selection criterion for the older driver (Zhan et al., 2013) and therefore fulfilling the requirement of ease of use during ingress/egress of vehicles is of commercial, as well as social, importance. It was therefore considered necessary to analyse the movement during I/E of vehicles by the older person and to consider the influence on I/E ease of use comfort levels of movement patterns adopted by the older person.

2. Materials and methods

The movement of 30 subjects (17 female, 13 male) during ingress and egress into 4 vehicles was measured. The age range of the subjects was 55–69 years with a mean age of 62 years and standard deviation of 4.2 years. The weight range of the subjects was 61 kg–120 kg with a mean weight of 79 kg and standard deviation of 18.2 kg. The height range was 1.52 m–1.93 m with a mean of 1.63 m and standard deviation of 0.073 m.

The ingress, seated posture and egress of the subjects was measured using the magneto-inertial Xsens MVN Awinda system consisting of 17 wireless motion tracking sensors. Each sensor contains 3 orthogonal linear accelerometers and 3 orthogonal gyroscopes. Angular drift about horizontal axes was eliminated by sensing the Earth's gravity and angular drift about the vertical axis was eliminated by using a magnotometer to sense the direction of the Earth's magnetic field.

Translational drift is more difficult to eliminate using an inertial measurement based system as there is, generally, no external reference. By default, the Xsens assumes a non-slip foot condition for the lower foot to remove drift in the horizontal plane and the Awinda sensors incorporate a barometer in each unit which can supposedly detect changes in altitude. The non-slip foot condition of the lower foot is not always valid, indeed the current study contains a situation when this assumption is violated, ie when the subject is seated in the vehicle and the feet are being lifted into the vehicle and the accuracy and repeatability of the altitude measurements are unknown. However for this study the absolute location, or even translational movements are not of significance but only the joint articulations and hence translational drift will not affect the results nor conclusions.

Xsens's MVN Studio software was used for the data capture. During the trial, the sensors attached to subjects were sampled at 60 Hz via a wireless interface and data stored on an i7 laptop personal computer.

A subject wearing the MVN Awinda system is shown in Fig. 1. The sensors are the small matchbox-sized boxes attached around the body. The sensors were attached to the subjects at the location listed in Table 1.

The vehicles used for the trials were large family cars (British market segment)/mid-size car (American market segment). Prior to the ingress/egress trials the subjects were instructed to adjust the seat and steering wheel positions to suit their driving style. The subjects were then instructed to open the vehicles driver's door, enter the vehicle at their own pace and sit in the driver's seat. When the subject had been seated in the driver's seat for approximately 3 s they were instructed to egress the vehicle which necessitated opening the driver's door and to close the door after their egression. The subject then moved to the next vehicle and continued until all 4 vehicles had been ingressed and egressed. The order in which the subjects encountered the vehicles was the same for all subjects; this was determined by the placement of the vehicles within the laboratory.

Between ingressing and egressing each vehicle, the sensors were re-calibrated to remove drift and motion artefacts resulting from any slippage of the sensors across the body. If there were any large movements of the sensors across the subjects' body during the trials, for example due to an impact contact with the vehicle structure, the sensors were repositioned before calibration and the trial repeated.

Immediately following the biomechanical trials, all of the subjects were asked to rate the ease of ingress and egress of each vehicle. The subjects were asked to assess the ease of ingress/egress based on an anatomical basis (eg individual joint articulation) and temporally (eg the moment of maximum comfort/discomfort during the ingress/egress event) but this was found to be confusing for the subjects and difficult to quantify. Therefore the subjects were asked to assess the ease of ingress/egress throughout the action on a scale of 1 (poor performance) to 5 (good performance).

It was assumed that the movement of the subjects could be represented by the linear superposition of a number of fundamental "modes" of motion where the number of modes is significantly less than the total number of degrees of freedom of the subject.

As an example of the concept of decomposing movements into fundamental modes, consider walking gait. Walking gait could be considered to be anti-phase swinging of straight legs. The motion does constitute a large component of the walking action but neglects many of the subtleties of gait and would be very impractical. Next introduce another movement which consists of some knee flexion with ankle dorsiflexion. The combined action of leg swing and knee/ankle shape would enable foot clearance from the ground during swing phase which would improve the gait relative to simple leg swinging but would still lack the finesse of real human gait. Therefore add more and more patterns of joint articulations until a motion indistinguishable from true gait is achieved. These patterns are the fundamental modes of gait. It is important to note that each of these modes typically contain articulations of numerous joints, all moving in phase.

This paper considers applying this deconstructive approach to analyse ingress/egress of vehicles and the task of identifying comfort rating versus movement correlation. This was undertaken by the identification of the appropriate linear combination of the modes of motion associated with vehicle ingress/egress which maximises their correlation to comfort assessments provided by the trials' subjects.

2.1. Theory/calculation

It will be assumed that the movement of the human body can be represented as a multi-rigid-body mechanism with $6 + 3^*N$ physical degrees of freedom where N is the number of joints each possessing 3 degrees of freedom. However rotation of some of these degrees of freedom may be restricted to virtually zero due to local anatomy. For example, the elbow can be modelled, for most applications, as a revolute hinge joint which releases the flexion/extension degree of freedom and the movement of the internal/