Kinematic Description of Hip and Knee Marker link system of Taxicab Operator

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Abstract
Driving automobile especially as applied to occupational driver is a very tasking activity involving a number of body segments coupled with high level of vigilance required to minimize occurrence of accidents and musculoskeletal disorder (MSD). A kinematic study of each segment of human operator of technological system help to evaluate the dynamics of the link system and internal forces required in driving activities. In this work Newton's second law of motion was applied to study the motion of human hip and knee marker link system and to develop bio-kinematic model for determining some kinematic parameters of the system. The model is capable of suggesting the variability of driver seat for effectiveness, safe and that minimise MSD in the operation of vehicle. Likewise the intensity, frequency and duration of exposure to harsh driving conditions can be regulated with appropriate threshold limit value (TLV) established.
Keywords: Kinematics, MSD, Threshold limit value, Biomechanics.

I. Introduction

Most of ergonomic research has been focused on Upper extremity link system which includes the Upper arm, Forearm and the hand segments. This is understandable judging from reported prevalence, severity and effect of reported musculoskeletal disorder at the part of human body. Research finding also show a relatively low percentage effect of injury cause by repetitive and overexertion of motion on the lower extremity. Reports of high percentage injuries to the lower extremity resulting in days off from work is prevalent among athletes, elevator operators, letter carrier, forest and conservation scientist, site supervisor, meter reader, driver, ushers, dancers, lawyer and preachers. These categories of workers experiences frequent movement of either one or all the segments of the link system and which contributes to mechanical stress and strain on the musculoskeletal system of lower extremity. Arthritis was diagnosed to have link with prolonged or repeated knee bending just as squatting or kneeling for more than 30minutes per day. This study consider the mechanical behavior of the thigh segment of the lower extremity as an effort to understand the kinematics of hip and knee maker motion as well as the internal forces course the motion. According to Szeto and Lam (2007), work-related musculoskeletal disorder is highly prevalent among bus drivers in Hong Kong. Other factors responsible for the increase in back pain among people apart from occupational risk factors include: age, fitness level, diet, heredity, race, presence of other diseases and cigarette smoking. (US Department of Health and Human Services, 2002).Physical stressors and workplace conditions that increase risk of injury or illness to the worker's musculoskeletal system are also referred to as ergonomic risk factors. Such factors that pose a risk of work related musculoskeletal disorders (WSDs) generally include repetitive and forceful motions; static muscle load and mechanical stress; vibration and temperature extremes; and awkward postures that arise from improperly designed equipment, tools, or work stations (Yassi 1997 and Yoonton, 1999). The workplace risk factors, along with personal characteristics (e.g., physical limitations or existing health problems) and societal factors, are thought to contribute to the development of WMSDs. Jobs or working conditions presenting multiple risk factors will have a higher probability of causing a musculoskeletal disorder. Often as a result of the slow onset, the micro-trauma is ignored until the symptoms become chronic and permanent injury occurs (Putz-Anderson, 1988). From a review of more than 2,000 studies of MSDs, reported in a NIOSH publication it was noted that compelling scientific evidence shows a consistent relationship between musculoskeletal disorders and certain work- related physical factors, especially at higher exposure levels (Yoonton 1999, OSHA 1999 and NIOSH 1997). Also Musculoskeletal disorder (MSD) has been found to affect significant proportion of the workforce and consequently is a major problem in several economic activity sectors in industrialized countries (Nastasia, Jette, Imbean, St-Vincent and Dnis 2008). The presence of a factor does not necessarily mean that the person doing the job is at excessive risk of injury and that job changes are worth their cost. When the presence of risk factors is combined with a history of repetitive trauma disorders among person doing that job, the risk of injury may be excessively high (Yoonton 1999, Armstrong and Chaffin 1997). The level of risk depends on the intensity, frequency, and duration of the exposure to these conditions and the individual capacity to meet the force or other job demands that might be involved. Moreover, the appearance of injuries and illnesses are often dependent on individual work factors including the length of employment, work station design, the training received by the employee, and employee work practices, including their rate of work (OSHA 1995).

1.1 Ergonomic Risks in Operating Automobile

Occupational driving is a highly demanding and responsible job in which both the driver and passengers are exposed to several occupational risks which includes fatigue, health damages by noise, vibration and toxic and irritating effects by atmospheric pollution, injury or death in case of fatal accident (Caragliu 2006). Automobile as a novel invention of human kind devised to ease the problem of movement of material, machine, men and commodities from one place to another. Ever since the advent of the first motorcar in 1885 fleets of models, makes and designs of vehicles have been introduced by various automobile companies. This was the result of improvements on the cars and attempts to enhance safety, efficiency and comfort of the users. In spite of all the effort made to improve the user friendliness of motor vehicles, there are still major complaints of health problems by millions of people worldwide (Pope, Magnusson, Lundstrom, Hulshof, Verbeek, and Bovenzi, 2002). Such problems include lower back pain and other musculoskeletal disorder. According to Pope and Novotny (1993), lower back pain (LBP) has been reported to be the main cause of sick leaves in developing world. Efforts made to understand the etiology of LBP as well as the cause are yet to yield a good result (Brinchmann, Johannleweling, Kilweg and Biggemann 1987, Leboeuf-Yde, Lauritzen and Lauritzen 1997, Okuribido. Shimble, Magnusson and Pope 2007).

Other studies demonstrating the association between occupational factors and low-back disorder have also been reported by [16] - [18]. Driving automobiles especially public transportation is a serious and tedious task that requires high level of responsibility on car operator (driver). The underline causes/risk factors involved in public driving have been studied and reported widely as being at an increased risk of LBP, whole body vibration and fatigue (Okuribido. Shimble, Magnusson and Pope 2007, Rosegger and Rosegger 1960, Bovenzi and Betta 1994, Magnusson, Pope, Wilder and Arekoug 1996, Jin, Sorock, Courtney, Liang, Yao, Matz, and Ge 2000, Kumar, Varghese, Mohan, Mahajan, Gulati and Kale 1999, Costa, Sartori, Facco and Apostoli. 2001, Mansfield and Marshall 2001). Several ergonomic factors have been identified as potential causes of fatigue and occupational stressors responsible for many uncomfortable experiences of drivers. Predominant occupational stressor in driving are postural stress (PS) whole body vibration, lower back pain, musculoskeletal disorder and fatigue.

1.2 Driving Postural

Posture is the position in which you hold your body upright against gravity while standing, sitting or lying down. Good posture plays key role in the prevention of back pain [26]. It involves training the body to stand, walk, sit and lie in positions while the least strain is placed on supporting muscles and ligaments during movement or weight bearing activity. Das and Grandy (1983) classified working posture involved in industrial operations into three type: standing, sitting and sitting and standing postures. Hadley and Harlegrave (2001) revealed that back pain in drivers is a major problem despite apparent advances in vehicle seat design and back care advice for use of a lumbar support to maintain good spiral posture. In the case of motorcycles the problem of low back pain could be more severe with absence of backrest for both driver and the passenger. Aaras, Horgen and Ro (2000) reported that constrained postures increase discomfort and health risks. Also the confinement of operator to fixed position with no room for adjustment of seat, throttle arm, front brake and clutch levers increases the trauma experienced by long distant operator of this automobile. Epidemiological studies have shown that vehicle drivers have a high prevalence low back pain which results from poor sitting posture held for long durations Hadley and Harlegrave 2001, Hannerz and Tuchsen 2001, Porter and Gyi 2002, Koda, Yesuda, Sugihara, Ohara, Udo, Otani, Hisashige and Aoyama 2000). Similarly, Porter and Gyi (2002) reported that the frequency of reported discomfort increased with higher annual mileage. Other studies conducted (Jin, Sorock, Courtney, Liang, Yao, Matz, and Ge 2000, Gruber and Ziperman 1974, and Backman 1983) have related increase in low back pain (LBP) among experienced driver with age. Kilbom and Person (1987) investigated into individual differences in working techniques and discovered that worker who worked in forward flexion of the neck and raised arm in a prolonged static postures ran a high risk of cervicobrachial disorders. Grandjean (1988) estimated that 50^{th} percent of adults suffer back aches during at least one period of life and stated that the main reason for frequent backaches is a pathological degeneration of the discs which is between the bony vertebrae and acts as an elastic cushion between vertebrae thus giving the spinal column it’s flexibility. Videman, Nurminen and Troup (1990) found that both sedentary work and heavy physical work were associated with abnormalities of the spine and that static seating posture causes discomfort. Graf, Guggenbuhl and Krueger (1993) and Graf, Guggenbuhl and Krueger (1995) reported more discomfort and chronic disorder among workers who sit in fixed postures. Movement reduces these risks (Aaras, Horgen and Ro 2000 and Kilbom 1987).

1.3 Ergonomic Biomechanics

The motions of human body and the forces responsible for the motions are aspect of human factors engineering referred to as ergonomic biomechanics. During driving activities some of human body segment are engaged in some physical works (Chaffin and Anderson 1991).

1.4 Occupational Biomechanics

Occupational biomechanics can be defined as the science concerned with the mechanical behavior of the musculoskeletal system and component tissues when physical work is performed. This is a system of assumptions about forces affecting the human body which provide an objective means for analyzing musculoskeletal functions in job activities. According to the study of Nordin and Frankin (1989), the general field of biomechanics used laws of physics and engineering concepts to describe motion undergone by the various body segments and the forces acting on these body segments during normal daily activities. The benefits of this knowledge can help ergonomists:

1. Evaluate the extent to which existing jobs place physical demands on the workers.
2. Simulate alternative work methods and determine potential reduction in physical demands if new work practices were instigated.
3. Provide a basis for employee selection and placement procedures [43](Phillips, 2000).

In this study, occupational biomechanics were used for evaluating the physical interactions of driver with control tools, within the cab to enhance the worker's performance while minimizing the risk of musculoskeletal disorders.

2. MATERIALS AND METHODS

Equation of mechanics is applied in the analysis of the complex system of motion of the human subsystem, using a simplifying approximation that reduces the complexity of human-subsystem and the corresponding system of motion to a “deterministic system”. The complex system of human physiological structure is simplified by partitioning the musculoskeletal systems into identifiable segments as shown in Fig. 1.

This approach opens up the process of biomathematical modelling of the driver-vehicle system. The process will be considered in the following steps:

(1) Selection of a spatial frame of reference
(2) Definition of the spatial coordinate systems
(3) Identification of Marker Locations of Thigh Segment representing the ends of 5^{th} and 95^{th} Percentile of Drivers Population.
(4) Determination of kinematic parameters

2.1 Selection of Spatial Frame of Reference

The three spatial frames of reference used in describing the positions of hip and knee of the operator in space are frontal plane, transverse plane and sagittal plane. For purpose of this study the sagittal plane of the thigh segment is used. The sagittal or profile plane which represents position and movement of driver’s body in two-dimensional plane as seen by an observer of person’s motion is shown in Fig. 2.

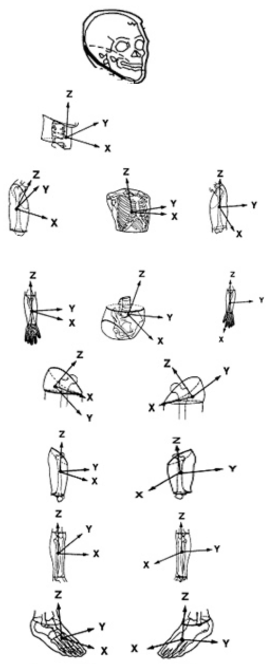


Fig. 1: Kinematic Representation Human Musculoskeletal Model. (Chaffin, and Anderson 1991, Philips 2000 and Onawumi 2009).

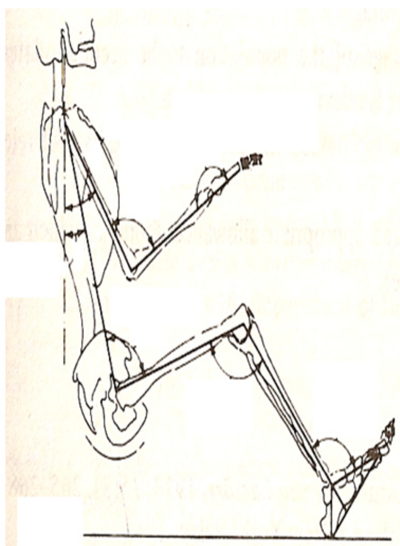


Fig. 2: The Upper, Thoracic and Lower Extremity Link-System (Adopted from Reference Sanders and McCormick 1993).

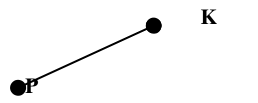
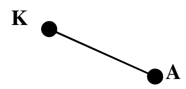
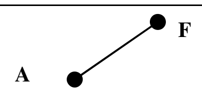
2.2 Definition of Spatial Coordinate System

The spatial coordinate system used has it's origin at the centre of mass of the operator's body. The coordinate system also accounts for linear and angular positions and the origin of the rectangular coordinate system is positioned so that the thigh segment is located within quadrant I and II.

2.3 Identification of Marker Locations of Thigh Segment representing the ends of 5th and 95th Percentile of Drivers Population.

The marker location representing individuals within the population of drivers is based on the anthropometric data for extreme marker link segment of thigh segment which is represented by buttock-knee high. This is used in developing a mock-up for drivers under consideration. The lower limb consists of the thigh, fore leg and foot (Table 1) presents the details of segments of human body and their link model.

Table1: Lower limb Segment, Marker and link Model

System	Segment	Marker link	Symbol	Link Model
Lower Limb	Thigh	The hip marker (P) and knee marker (K)	PK	
	Fore leg	Knee marker (K) and ankle marker (A)	KA	
	Foot	Ankle marker (A) and ball of the foot marker (F)	AF	

2.4 Determination of Kinematic Parameters

Ergonomic biodynamics of driver's thigh segment while operating the vehicle involve the generation of internal forces about the joints of the segment which then results in the external motion of the affected segments. The internal forces are determinable from the kinematics and kinetic parameters of the segment motion.
The following kinematics parameters are used to describe the thigh motions from profile plane.

- The horizontal position (x) of the segment's centre of mass (m)
- The vertical position (y) of the segment's centre of mass. (m)
- Horizontal linear velocity (v_x) of the segment's centre of mass. (m/s)
- Vertical linear velocity (v_y) of the segment's centre of mass. (m/s)
- Horizontal linear acceleration (a_x) of the segment's centre of mass. (m/s^2)
- Vertical linear acceleration (a_y) of the segment's centre of mass. (m/s^2)
- Angle of the segment in the x-y plane. (degree)
- Angular velocity (ϖ) of the segment in the x-y plane. (rad/s)
- Angular acceleration (α) of the segment in the x-y plane. (rad/s^2)

A. Segment Analysis and Model Formulation

In this case both the centre of mass location and angle orientation for the segment are determined using the anthropometric data of Nigerian taxicab driver (Onawumi, 2009).

B. Segment Angle of Orientation

The segment analysis involves the determination of the point along the segment line at which the centre of mass is located as well as the angle at which the segment line is oriented. The centre of mass is also determined while the angle of orientation is obtained with the two known marker coordinate space. The i^{th} and j^{th} markers represent the inferior and superior end of the segment. A rectangular coordinate system is used in describing the actual position of the segment. When the inferior marker is positioned leftward and the superior marker the rightward as shown in Fig. 3 the segment is considered to appear in quadrant 1 of the polar coordinate system. The angle of orientation (θ) of the segment which is defined in term of the inferior marker is considered to vary between 0 and $\pi/2$ radians. Hence:

$$\tan\theta = \frac{|y_j - y_i|}{|x_j - x_i|} \quad (1)$$

Where:
x_i = horizontal position of i[th] marker
x_j = horizontal position of j[th] marker
y_i = vertical position of i[th] marker
y_j = vertical position of j[th] marker

From equation 1 θ may be defined (in radian) as

$$\theta = \tan^{-1}\left[\frac{|y_j - y_i|}{|x_j - x_i|}\right] \quad (2)$$

The case when the inferior marker is repositioned rightward and the superior marker likewise repositioned leftward as shown in Fig. 4 the segment is considered to appear in quadrant 2 of the polar coordinate system. The angle of orientation (φ) of the inferior marker is considered to vary between π/2 and π radians.

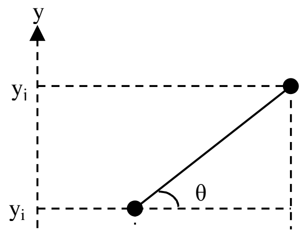


Fig. 3: Segment with i[th] marker positioned leftward and j[th] positioned rightward

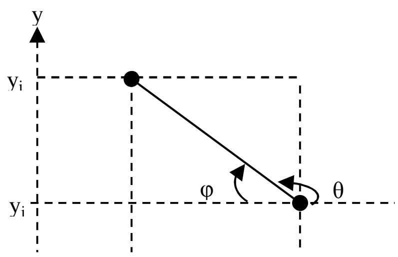


Fig. 4: Segment with i[th] marker positioned rightward and j[th] positioned leftward

Hence with the angle of orientation extended to quadrant 2 so that

$$\varphi = \tan^{-1}\left[\frac{|y_j - y_i|}{|x_j - x_i|}\right] \quad (3)$$

$$\theta_i = \pi - \varphi_i \quad (4)$$

I. Determination of Thigh Mass and Moment

Given the length of thigh segment with a variable segment mass (m_i) is a function of the volume of that section (v_i). The segment experiences two types of moment during operation. These are translation moment and rotational moment. The segment is assumed to be in dynamic equilibrium and the relationship between the force exerted by the segment and linear acceleration in accordance to the established Newton's laws.

J. Centre of Mass

Each segment of driver's body segment listed in Table 1 represents a structure of distributed mass. The determination of centre of mass for body segments is presented using the case of thigh segment. For uniform density (d) segment the mass of any given section is a function of the volume of that section (v_i) and expressed as:

$$m_i = d v_i \quad (5)$$

The mass of the entire segment $\overline{m}$ is therefore:

$$\overline{m} = d\sum_{i=1}^{n} v_i \quad (6)$$

The centre of mass of the masses is located at $\overline{x}$ having the same net gravitational moment of force about the left edge as shown in Fig. 5. Hence:

$$\overline{m}\,\overline{x} = \sum_{i=1}^{n} m_i x_i \quad (7)$$

Rearranging to solve for the location of the segment centre of mass ($\overline{x}$):

$$\overline{x} = \frac{1}{\overline{m}} \sum_{i=1}^{n} m_i x_i \quad (8)$$

It is also useful to consider the situation where the centre of mass of the segment is located at the right edge of the segment as shown in Fig. 6 denoted by $\overline{x}'$. The individual section masses are multiplied by their individual moment arms so that the centre of mass located at $\overline{x}'$ from right edge of the segment would be:

$$\overline{m}\,\overline{x} = \sum_{j=1}^{n} m_j x_j \quad (9)$$

Rearranging to solve for the location of the segment centre of mass ($\overline{x}$):

$$\overline{x} = \frac{1}{\overline{m}} \sum_{i=1}^{n} m_i x_i \quad (10)$$

$$\overline{m}\,\overline{x}' = \sum_{j=1}^{n} m_j x_j \quad (11)$$

$$\overline{x}' = \frac{1}{\overline{m}} \sum_{j=1}^{n} m_j x_j \quad (12)$$

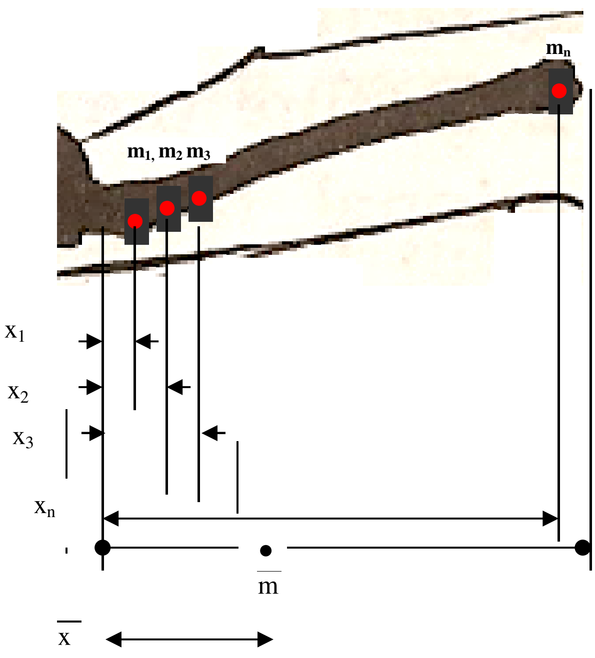


Fig 5: Thigh Segment representing a Structure with Distributed Mass

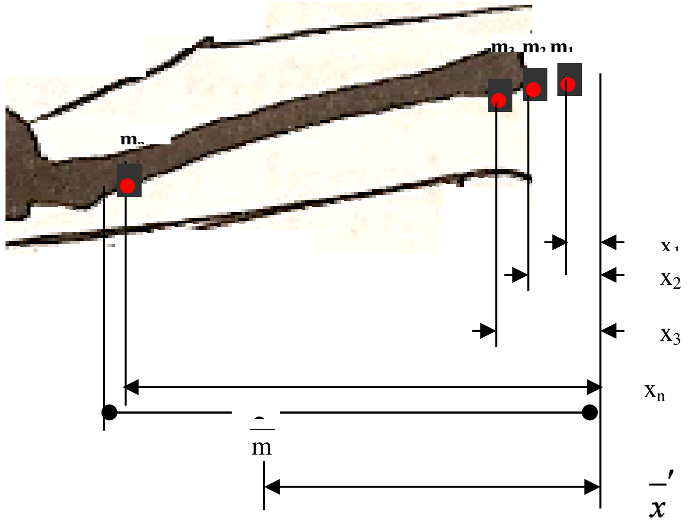


Fig. 6: Variable Segment Mass for Thigh Segment

The sum of $\bar{x}$ (from equation 7) and $\bar{x}'$ (form equation 9) is:

$$x + \bar{x}' = \Delta x \tag{13}$$

Fig. 7 shows the axial and rectangular coordinate space when segment angle (θ) is between 0^0 and $\pi/2$ (I the first quadrant) respectively. Equations 14, 15 and 16 represent the vertical coordinate for the centre of mass ($\bar{y}_i$) with respect to the distal end of the segment or the horizontal end or segment.

$$\bar{y}_i = y_i + a' = y_i - b \tag{14}$$

$$a' = \left|y_j - y_i\right|\bar{x}_d \tag{15}$$

$$b' = \left|y_j - y_i\right|\bar{x}_p \tag{16}$$

The horizontal coordinate of the centre of mass is presented by equations 17, 18 and 19.

$$\bar{x}' = x_i + a'' = x_j - b'' \tag{17}$$

$$a'' = \left|x_j - x_i\right|\bar{x}_d \tag{18}$$

$$b'' = \left|x_j - x_i\right|\bar{x}_p \tag{19}$$

Fig. 8 represents the segment in coordinate space when the segment angle (θ) is between $\pi/2$ and π (second quadrant). The distal end is now located at the rightward end while the proximal end is leftward. Equation 20 show the segment centre of mass for the case where the angle of orientation is located between 90^0 and 180^0.

$$\bar{x}_i = x_i + b'' = x_j - a'' \tag{20}$$

Each set of marker positional data is separated in time by a finite time interval Δt. The calculation of velocity displacement data then simply requires that the finite difference (displacement) data Δx is divided by the finite time (Δt) interval. Since we require velocity at a particular point in time (at ith time), this can be accomplished by subtracting the position at time i-1 from the position at time i+1 and divided by the corresponding time interval.

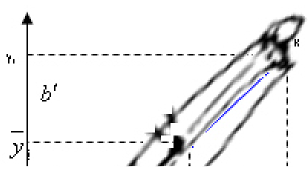


Fig. 7: Thigh Segment in Rectangular Coordinate Space when Orientation angle is within Quadrant 1 ($0^0 < \theta < 90^0$)

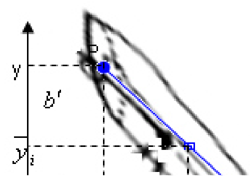


Fig. 8: Thigh Segment in Rectangular Coordinate Space when Orientation angle in within quadrant 2 ($90^0 < \theta < 180^0$)

The interval velocity for the segment centre of mass along the vertical axis would be:

$$v_{y_i} = \frac{\overline{y}_{i+1} - \overline{y}_{i-1}}{2\Delta t} \quad (21)$$

The horizontal velocity of the segment centre of mass would be:

$$v_{x_i} = \frac{\overline{x}_{i+1} - \overline{x}_{i-1}}{2\Delta t} \quad (22)$$

The vertical acceleration of the segment centre of mass can also be calculated from three adjacent positional data points (with time interval Δt between any two adjacent sets). Expressing the midpoint method for acceleration at the i[th] time point:

$$a_{y_i} = \frac{v_{y_{i+\frac{1}{2}}} - v_{y_{i-\frac{1}{2}}}}{\Delta t} \quad (23)$$

Where

$$v_{y_{i+\frac{1}{2}}} = \frac{\overline{y}_{i+1} - \overline{y}_i}{\Delta t} \quad (24)$$

and

$$v_{y_{i-\frac{1}{2}}} = \frac{\overline{y}_i - \overline{y}_{i-1}}{\Delta t} \quad (25)$$

With respect to the vertical acceleration of the segment centre of mass substituting equation (24) and (25) into equation (23) and simplifying, the vertical acceleration becomes:

$$a_{y_i} = \frac{\overline{y}_{i+1} - 2\overline{y}_i + \overline{y}_{i-1}}{(\Delta t)^2} \quad (26)$$

Similarly for the horizontal acceleration of the segment centre of mass:

$$a_{x_i} = \frac{\overline{x}_{i+1} - 2\overline{x}_i + \overline{x}_{i-1}}{(\Delta t)^2} \quad (27)$$

With the orientation angle (θ) of the segment as obtained in equation (2), the segment angular velocity (ω) and angular acceleration (α) may be determined:

$$\omega_i = \frac{\theta_{i+1} - \theta_{i-1}}{2\Delta t} \quad (28)$$

and

$$\alpha_i = \frac{\theta_{i+1} - 2\theta_i + \theta_{i-1}}{(\Delta t)^2} \quad (29)$$

K. Link-Segment Systems Simulation

Each segment kinematics and kinetic characteristics were determined for varying positional coordinate using the equation that model the system behaviour. The basic inputs for the determination of kinematic parameters used to describe body segment viewed from profile view as obtained from kinesiological data and anthropometric data are vertical and horizontal locations of both inferior and superior markers for varying finite time interval. Other measurements to be supplied include the segment density and volume. These data were further used to calculate the angle of orientation of the segment under study the segment center of mass, radius of gyration, moment of inertia at the center of mass and other segment kinetic properties.

The program for the execution of the equations derived above (equations 1to 29) is written in C^+ programmimg language.

L. Simulation Algorithm

C^+ programming language will be used to describe the sequence of interactive algorithm that is aimed at calculating the unknown dynamic properties of the studied driver's body segment.

The number of sections of the link segments are first supplied then the segment proximal and distal positional coordinate. With these the angle of orientation is calculated. The volume of the segment section(s) as well as the density(ies) of identified sections of the segment are also supplied in order to calculate the total segment mass. As position changes the finite difference in time are measure and corresponding velocity and acceleration were calculated. Likewise for a small change in angle of orientation, the angular velocity angular acceleration and then the moment of inertial for both the proximal and distal end of segment were calculated.

3. Application

Linier and angular position vector for the proximal and distal end of the thigh segment viewed from sagittal plane was generated using AUTOCAD 2009 package. The origin of rectangular coordinate system was positioned so that the thigh segment under consideration is within quadrant I and II. The package is used in conjunction with driver's anthropometric data collected on the studied segment for both 5th and 95th percentile of different functional anthropometric measurements. Table 2 present the data used to execute biodynamic equations derived in order to obtained the derived kinematic parameters of the subject used as follows.

Table 2: Input data for the thigh motion

Input variable description	**Value**
Distal (x, y) (cm)	186, 120
Proximal (x, y) (cm)	250, 140
Segment length (cm)	61.5
Segment volume (cm^3)	1.3, 1.1
Density (g/cm^3)	1.05
x-coordinate	130, 140
Xi, xi-1, xi+1	120, 110, 140
Yi, yi-1, yi+1	186, 200, 250

Table 3: Output variables

Kinematic variables	**Value**
Horizontal linear velocity (m/s) Vxi	33.7
Vertical linear velocity (m/s) Vyi	71.9
Horizontal linear acceleration (m/s^3) axi	12.6
Vertical linear acceleration (m/s^3)	45.4
Angular velocity of the segment in the x-y plane. (rad/s)	-0.00787
Angular acceleration of the segment in the x-y plane. (rad/s^2)	0.0417
Sum of force in x coordinate	82
Sum of force in y coordinate	295
Moment of inertia	156
Radius of gyration	4.9

4 Conclusions

The kinematics study of human body parts especially those that are critically involved in occupational driving activities and belonging to user population outside the country of manufacture of the automobile is an highly necessary with the current developments of rapidly advancing technology of automobile and it growing market in the developing nations. The link segment simulation was developed to provide the needed parameters which aid in the establishment of related threshold limit values for consideration in the design of drivers work system using anthropometric variables of Nigerian occupational drivers as basic input.

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