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ESTIMATION OF MASS MOMENT OF INERTIA OF HUMAN BODY, WHEN BENDING FORWARD, FOR THE DESIGN OF A SELF-TRANSFER ROBOTIC FACILITY

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Abstract

Knowledge of Mass Moment of Inertia of human body and its segments are necessary for various problems in biomechanics and its applications. This paper focusses on the estimation of Moment of Inertia of a human body when bending forward, which is needed for designing a robotic self-transfer facility for elderly and disabled. This paper also covers a brief review on studies of different anthropometric data like mass of the body segments, Centre of Mass, radius of gyration, etc. Using these data and certain assumptions, Mass Moment of Inertia of human body bending forward is estimated by applying laws of basic mechanics. This estimated value is then validated using a solid modelling CAD software.

Keywords: Mass moment of Inertia, Centre of gravity, Radius of gyration, Anthropometry

1. Introduction

When there is a change of state in the movement of a human body, then the body always experiences a resistance called 'Inertia'. Mass, density, radius of centre of mass, moment of mass, moment of inertia, radius of gyration and deviation moments are the inertial quantities [1]. These inertial quantities of human body are essential for quantitative analysis of human motion [2]. Among the above quantities, Mass Moment of Inertia (MOI) has considerable significance. All these inertial quantities are collectively known as anthropometric data. Anthropometry is a branch of anthropology that emphasises the physical measurements of human body so as to determine differences in individuals and roups [3]. Mass, Centre of Gravity (COG) and radius of gyration of each body

Nomenclatures

I	Mass Moment of Inertia of the body/segments, kg m^2
k	Radius of gyration of the segments, m
L	Length of the segments, m
M	Mass of the body /segment, kg
r	Distance between COG of each segment and COG_{TORSO}, m

Abbreviations

COG	Centre of Gravity
MOI	Mass Moment of Inertia

g segment are the inertial quantities required for the estimation of MOI applying laws of basic mechanics. The objective of this paper is to theoretically estimate MOI of human body when bending forward, which can be used for torque calculation in designing a robotic self-transfer facility for the elderly and disabled.

The anthropometric table which contains inertial quantities is mostly compiled from data obtained by investigating cadavers or living individuals [4, 5, 6]. Huge interest has been shown by various investigators over two centuries to determine inertial quantities of human body and its segments [5]. This resulted in the evolution of a wide variety of techniques for determining these quantities. In the earlier seventeenth century, Borelli determined centre of mass of human body by stretching out the subjects on a platform supported on a knife edge and moving the platform until it is balanced [5]. In 1836, Weber brothers came up with more improved and accurate technique where the platform was supported at its COG and the human body alone moved until the platform began to tilt. It was Harless in 1860, who repeated Weber's technique on two cadavers to determine COG of individual body segments. In 1889, Braune & Fischer reported their findings on weight, volume, COG of body and its segments based on the analysis obtained from a study of three cadavers. Unlike the previous techniques, Braune & Fischer had kept the cadavers frozen so as to reduce fluid losses to minimum [5] . The data provided by Braune & Fischer were almost accurate and had been extensively used by scientists since then. In 1969, Clauser et al. determined anthropometric quantities of body segments from thirteen preserved male cadavers [5].

As human body is composed of tissues that get distorted when body changes position and lack of simple single measurement technique, determining MOI is a difficult task. In most cases the segments of the body are assumed to be rigid. In 1892, Braune & Fischer measured MOI about the longitudinal axis and latitudinal axis [6]. Again in 1906 Fischer reported a study of MOI of human body and its segments [5, 6]. In 1955, Dempster conducted studies on eight cadavers and reported data on weight, volume, COG and MOI of each segments of the human body. The data obtained by Braune & Fischer, Fischer and Dempster were compiled and prepared as a series of regression equations for predicting segment weights from body weights by Barter in 1957. Studies of Santchi et al. proved that in a three dimensional body, more than one axis can pass through the COG, which results in more than one MOI. They measured three MOIs about three orthogonal axes defined as intersection of three anatomical planes of the body i.e. sagittal, frontal and transverse plane.

Table 1 contains segment weights as percentage of body weight reported by different investigators. Table 2 contains segment lengths as percentage of body height as compiled by Hall [7, 8]. Segment COG expressed as percentage of segment length is provided in Table 3. Figure 1 shows COG of each segment of an adult male human body [7]. Table 4 contains radius of gyration of each segment of the human body [1]. With the help of these values, MOI of human body bending forward is estimated in this paper.

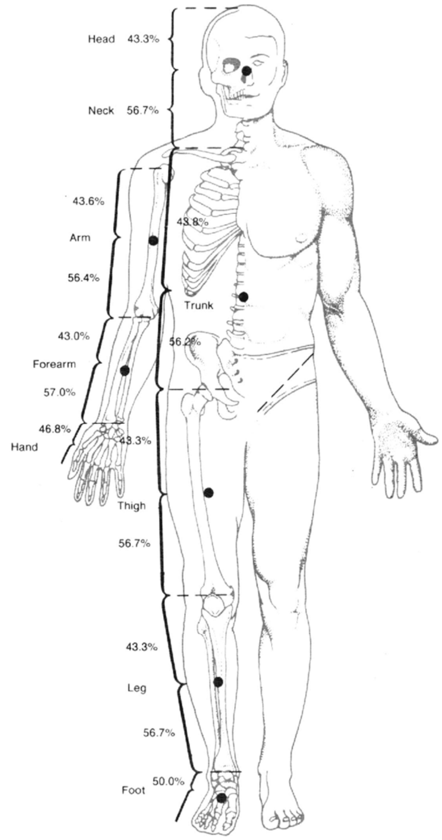

Fig. 1. COG of each segment of an adult male human body [7].

Table 1. Segment weights as percentage of body weight.

Segment	Investigators					
	Harless	Braune &Fischer	Fischer	Dempster	Clauser et al.	Hall
Head & Neck	7.6	7.0	8.8	8.1	7.3	8.2
Torso	44.2	46.1	45.2	49.7	50.7	46.84
Upper arm	3.2	3.3	2.8	2.8	2.6	3.25
Lower arm	1.7	2.1	-	1.6	1.6	1.8
Hand	0.9	0.8	-	0.6	0.7	0.65
Thigh	11.9	10.7	11.0	9.9	10.3	10.5
Calf	4.6	4.8	4.5	4.6	4.3	4.75
Foot	2.0	1.7	2.1	1.4	1.5	1.43

Table 2. Segment lengths as percentage of body height [7, 8].

Segment	Length in percentag
Head & Neck	10.75
Torso	30.00
Upper arm	17.20
Lower arm	15.70
Hand	5.75
Thigh	23.20
Calf	24.70
Foot	14.84

Table 3. Distance of segment centre of gravity from proximal end as percentage of segment length.

Segment	Investigators	
	Dempster	Hall
Head & Neck	43.3	56.7
Torso	49.5	56.2
Upper arm	43.6	43.6
Lower arm	43.0	43.0
Hand	49.4	46.8
Thigh	43.3	43.3
Calf	43.3	43.4
Foot	42.9	50.0

Table 4. Radius of gyration of body segments as a percentage of segment length [1].

Segment	Radius of gyration according to the axis		
	Sagittal	Frontal	Longitudinal
Head & Neck	30.3	31.5	26.1
Torso	48.2	38.3	46.8
Upper arm	32.8	31.0	18.2
Lower arm	29.5	28.4	13.0
Hand	28.5	23.3	18.2
Thigh	26.7	26.7	12.1
Calf	28.1	27.5	11.4
Foot	25.7	24.5	12.4

The remaining content of the paper is organised as follows: Section 2 addresses the need for estimation of MOI of human body bending forward. Section 3 covers the estimation of MOI. Validation through a solid modelling CAD software is addressed in section 4 and section 5 contains concluding remarks.

2. Need for Estimation of MOI

The mechanical design of a robotic self-transfer facility, a value addition to a wheel chair, involves estimation of MOI of human body in bending forward posture. The conceptual design of a proposed self-transfer facility is illustrated in Fig. 2. The self-transfer facility consists of a saddle which is erected from the centre of a turntable using a length adjustable arm. The length adjustable arm could be tilted upon actuation. The transfer from the wheel chair to another chair or a commode can be divided into five discrete stages of motion. To initiate the transfer, i.e. during stage 1, subject leans forward and places his/her chest on the saddle. During stage 2, the subject is raised by elongating the arm while simultaneously tilting the arm vertically as shown in Fig. 2. At stage 3 the arm would have attained 90 degrees position and the subject's chest would be resting on the saddle in a bending forward posture. In stage 4, the turntable mechanism could be rotated, until the subject's back is positioned towards the chair or the commode. Finally at stage 5, the arm is shortened and tilted to lower the subject's body to place him/her on the chair.

During stage 4, the subject is in bending forward posture placing his/her chest on the saddle and the turntable needs to be rotated. The torque required to rotate the turntable depends on MOI of the subject on the turntable, about the axis of rotation.

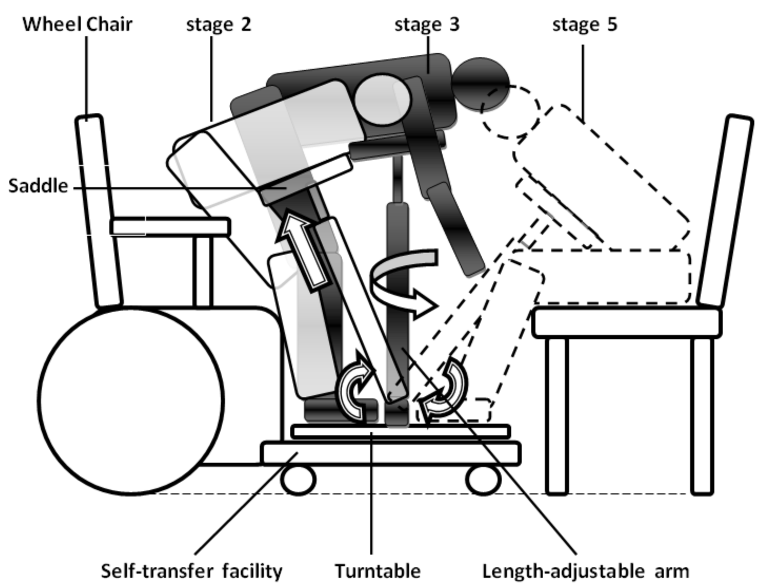

Fig. 2. Operation of self-transfer facility.

3. Estimation of MOI

The MOI of the whole body in bending forward posture about the vertical axis of the length adjustable arm needs to be estimated. The stick diagram of a human body bending forward with the locations of the COG of each segment and associated MOI is shown in Fig. 3.

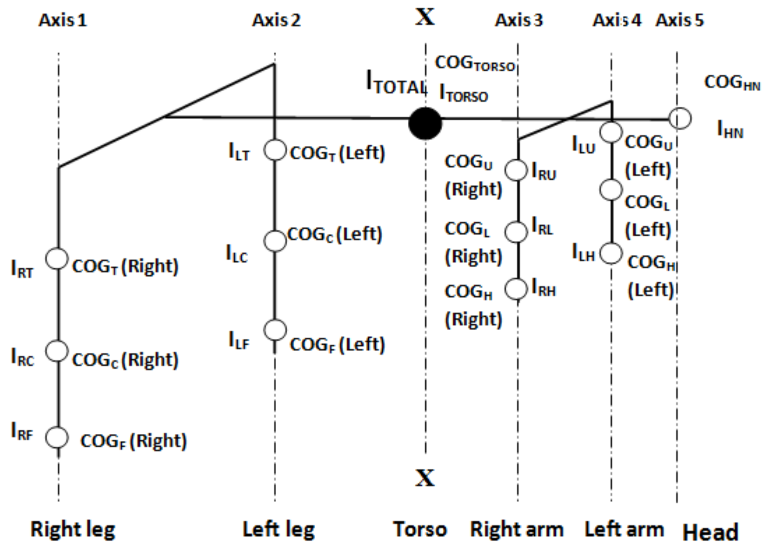

Fig. 3. Stick diagram of a human body bending forward with COG and MOI of each segment specified.

It is assumed that the segments of the legs viz. thigh, calf and foot have the same vertical axis. Similarly segments of the arms namely upper arm, lower arm and hand are assumed to be along a single axis. Left arm and left leg segments are symmetric to right arm and right leg segments respectively. Referring to Fig. 3, Right leg and left leg are along vertical axes axis 1 and axis 2 respectively. Axis 3 and axis 4 are the vertical axes of right arm and left arm. Axis 5 is the vertical axis of the head & neck and the vertical axis passing through COG of torso is taken to be axis-x

Studies show that the average mass and the average height of males are slightly higher than that of the females [10] and hence anthropometric data of standard human male is considered for estimation. A male subject of height 1.74 m and mass 74 kg is taken for estimation purpose. The segment weight and COG values compiled by Hall [8], specified in Table 1 and Table 3 are used for estimation, as these values are most widely accepted. From Table 4, radius of gyration in longitudinal axis is considered during calculation of MOI of leg segments and arm segments while radius of gyration in sagittal axis is considered for torso and head. This is because, when a person bends forward, his sagittal axis becomes parallel to the longitudinal axes. Figure 4, taken from [9], depicts various planes and axes with respect to human body.

MOI of human body in the bending forward posture can be estimated from the anthropometric data [1, 7, 8], of a standard human male, taken from Tables 1-4. First MOI of each body segment is calculated. Using parallel axes theorem, MOI of individual segments about the axis of rotation i.e. x-axis are determined and finally, total MOI is calculated by adding all the MOI including that of the torso. The proposed methodology of estimation of MOI of a human body in the bending forward posture can be applied to both the genders of any human model, as the variations from the anthropometric parameters of the standard human model are only minimal.

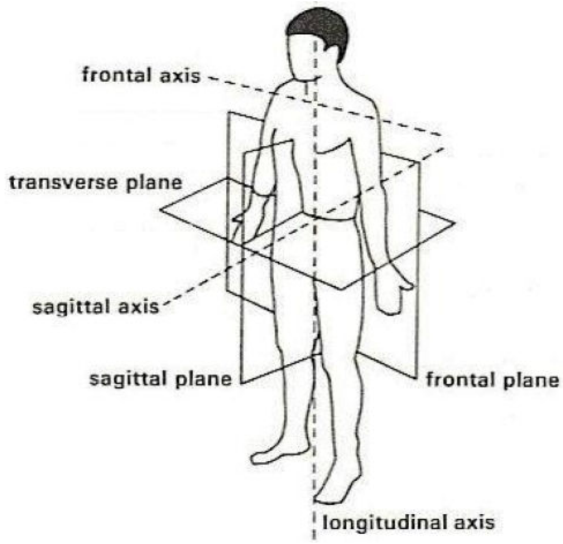

Fig. 4. Human body planes and axes [9].

3.1. MOI of body segments about its own COG

MOI of each body segment can be estimated corresponding to the anthropometric data related to each segment. For example, estimation of MOI of Head & neck is as follows:

- Length of head & neck is taken to be 10.75% of height as given in Table 2 and is found to be $L_{HN} = 0.19$ m.
- Mass of head & neck is taken to be 8.2% of total mass as given in Table 1 and hence, $M_{HN} = 6.07$ kg
- Radius of gyration of head & neck in sagittal axis is 30.3% of segment length as per Table 4 and therefore, $k_{HN}= 0.06$ m
- Now MOI of head and neck can be calculated using the equation-

$$I_{HN} = M_{HN}\, k_{HN}^{\ 2} = 6.07 \text{ x } (0.06)^2 = 0.02 \text{ kg m}^2$$

Following the same procedure MOI of torso, hand segments and leg segments are determined and the results are provided in Table 5. Radius of gyration in longitudinal axis is considered for all the segments other than head & neck and torso.

3.2. MOI of each segment about the axis of rotation

3.2.1. Location of COG of each segment

COG of each segment can be located by determining the distance from the proximal end using the fractions provided in Table 3. For example, the COG of

Head & neck is determined to be at 0.11 m from the proximal end which is 56.7% of L_{HN}= 0.19m. Similarly COG of all other segments are located and the distances are furnished in Table 5.

3.2.2. Determination of offset

The offset (*r*) is the shortest distance between the x- axis (passing through the COG of torso) and the other axis passing through the COG of segment under consideration. The top view of the stick diagram of a human body bending forward is given in Fig. 5. 'A' is the distance of COG of the head and neck from shoulder joint and is 0.11 m for the chosen example. The distance between the COG of torso from shoulder joint is denoted by 'B' and the value is 0.23 m. Therefore, the offset distance between the axis of head & neck and the axis of rotation, denoted by r_{HN}, is the sum of 'A' and 'B' resulting in 0.34 m. 'C' is the distance from the hip joint to the COG of torso and is 0.29 m in this particular case. L_{HIP} and L_S are the dimensions of the hip and the shoulder having the values 0.30 m and 0.40 m respectively. By constructing right angled triangles as shown in Fig. 5, r_{ARM} and r_{LEG} are determined to be 0.30 m and 0.33 m respectively.

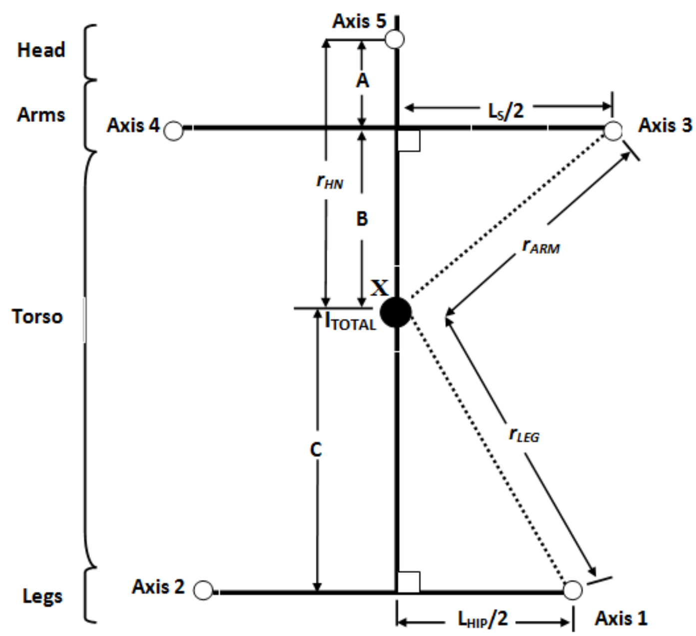

Fig. 5. Top view of the stick diagram of human body bending forward.

3.2.3. Application of Parallel Axes Theorem

The MOI of different body segments about the axis of rotation (x-axis) can be estimated using Parallel Axes Theorem. The MOI of head and neck about the axis of rotation is found as shown below.

$I_{HN}' = I_{HN}+(M_{HN}\ r_{HN}^2)= 0.02+ (6.07 \text{ x } 0.34^2) =0.72$ kg m^2

Similarly, MOI of all the other segments are found about the axis of rotation and is provided in Table 5.

Finally total MOI is calculated by adding MOI of segments of both arms (I_U', I_L', I_H') and legs (I_T', I_C', I_F') about x-axis, MOI of head & neck about x-axis (I_{HN}') and MOI of torso (I_{TORSO}). Thus the MOI of the total human body bending forward is estimated to be 6.41 kg m^2 for the chosen case.

Table 5. Anthropometric data of various body segments of subject under consideration.

Segment	Length-L (m) †	Mass-M (kg)	Radius of Gyration– k (m)	MOI – I (kg m^2)	COG location (m) †	MOI about x-axis -I' (kg m^2)
Head & Neck	0.19	6.07	0.06*	0.02	0.11	0.72
Torso	0.52	34.66	0.25*	2.17	0.29	-
Upper arm	0.30	2.40	0.05	6×10^{-3}	0.13	0.22
Lower arm	0.27	1.33	0.04	2.13×10^{-3}	0.12	0.12
Hand	0.10	0.48	0.02	1.92×10^{-4}	0.05	0.04
Thigh	0.40	7.77	0.05	0.02	0.17	0.87
Calf	0.43	3.52	0.05	8.8×10^{-3}	0.19	0.39
Foot	0.26	1.05	0.03	9.45×10^{-4}	0.13	0.12

† measured from proximal end
* considering sagittal axis

4. Validation of the calculated result

In order to validate the estimation of MOI detailed in the previous section, a full body manikin, of same mass, 74 kg and same height, 1.74m, is considered. The manikin is modelled in Solidworks, a solid modelling CAD software in forward bending configuration as shown in Fig. 6. As specified in earlier sections, the human body at this posture is expected to rotate about a vertical x-axis which passes through the chest. Thus an output coordinate system is specified with x-axis at COG of torso, 0.29 m from the hip joint. Now the mass properties of the manikin in the specified posture are obtained about this output coordinate system. The MOI of the manikin about vertical x- axis, I_{XX} , determined by the software is 6.72 kg m^2 as shown in Fig. 6.

The estimated MOI value of 6.41 kg m^2 as detailed in Section. 3 is closer to the value of 6.72 kg m^2 determined by the Solidworks with a small deviation of 4.6%. Hence the methodology used for estimation of MOI is valid and acceptable for calculation of torque requirement of the turn table. The deviation of 4.6% may be attributed to the following two reasons. (1) The simplified assumption that the longitudinal axes of all the segments of the limbs fall in a single line. (2) The variations in shape and size of segments are not accounted in the estimation of MOI.

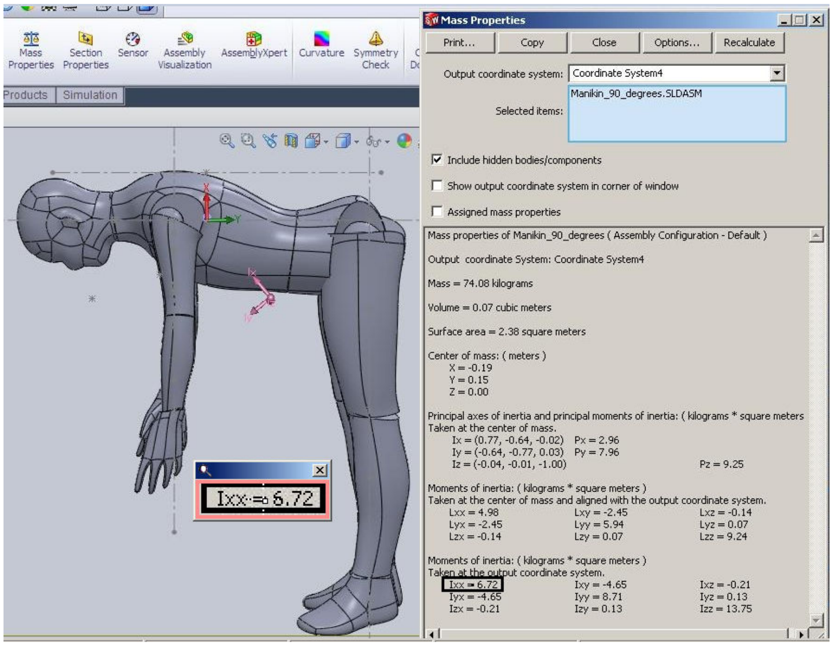

Fig. 6. Screen shot of manikin in the forward bending posture.

5. Conclusion

The MOI of a human body bending forward is an important parameter to be considered for designing a self-transfer robotic facility. The self-transfer facility consisting of a turntable, which carries a subject bending forward placing his/her chest on a saddle elevated from the centre of the turntable rotates about its own axis. The torque required to rotate the turntable depends on MOI of the subject on the turntable. The MOI of a human body, in the required posture, is estimated using basic laws of mechanics with certain assumptions. Different anthropometric data required for the estimation of MOI are chosen after reviewing various data compiled by various investigators. The validation of the estimated MOI is done by modelling a manikin, of same weight and height in Solidworks. The estimation is found to be valid and acceptable for calculation of torque requirement of the turn table. Any how the selection of motor may employ a suitable factor of safety after the torque requirement is carried out from the MOI and the required angular acceleration.

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