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Estimation of Joint Torque and Power Consumption during Sit-to-Stand Motion of Human-being Using a Genetic Algorithm

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Abstract

A model of human lower limb along with body has been drawn having a presumed body height and body mass index. Different ranges of joint angles of human legs and body have been taken to simulate the sit-to-stand motion. The kinematic analysis is done by varying joint angles over time. The dynamic studies have been carried out for different joints. Torque and power consumption have been calculated. Using a genetic algorithm, optimal solutions for joint torque and power consumption have been obtained. The dynamic balance of human body system during sit-to-stand motion has also been maintained while carrying out the optimization. Another attempt has been made in order to get optimum torque and power consumption in minimum time by treating it as a multi-objective optimization problem. Thus, a Pareto-optimal front of solutions has been obtained.

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Keywords:Genetic algorithm;Objective fucntion;Multi-objective optimization;Zero Moment Point ;Dynamic Balance Margin;

1. Introduction

Sit-to-stand (STS) motion is the second earliest locomotion process of a human baby after he/she learns the crawling. Initially, he/she tries to sit and then starts to stand. However, in the first attempt, he/she may not be successful. There are a number of trials between the first attempt and first success of getting up. By conducting different attempts and learning from the past mistake or failure, through a rigorous training, finally, a human baby

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learns how to stand from sitting posture. Mathematically, the whole process of learning can be thought as an optimization one. A human of certain height and body mass index, has certain bone strength, ability to consume power and torque capacity. In order to stand from sitting condition, a human need to stand in such a way that these torque and power consumption values should be minimized. Not only that, dynamic balance also must be maintained throughout the whole process of STS motion. Now, if a human wants to stand from sitting within a desired time, the required torque and power consumption along with dynamic stability will be dependent on it. So, in order to stand in minimum time by minimizing the torque and power consumption, optimization technique can be used effectively to determine the optimal solution. Now, there is a certain range of angle for each joint of a human being. There are large numbers of combinations of different joint angles and human must choose the specific combination among these, for which the joint torque and power consumption will be minimum and dynamic balance will be maintained. To perform the above optimization process, a global search technique like genetic algorithm may be a natural choice.

2. Related work

A plenty of studies, both experimental as well as theoretical on the analysis of STS motion had been reported so far. To make the suitable STS motion, it is required to have information of ground reaction force. Using motion capturing high speed camera, motion tracking software and force plate, minimum force had been measured by Kamaruddin et al.[1] in their study. Likewise, Millington et al.[2] also evaluated the different phases of STS by using piezoelectric force plates. The muscle activity was observed by electromyography. The purpose of the characterization was to identify the different problems faced by older persons during STS. Mombaur[3] formulated an optimization problem to simulate "sit-to-stand transfer" as two phase multi-body system model. Though the system did not consist of an appropriate dynamic balance model, it could be utilized to design rehabilitation device for STS. A synergy analysis was carried out by An et al.[4], where four synergies were extracted. Those were preparation of motion; rising along with forward movement of hip and center of mass of body; upper body lifting accompanied by ankle flexion and finally, posture stabilization after the standing up. The usage of arm, speed variation and chair height have significant influence in synergy construction and further research on these will make the study more effective to older people for detecting difficulty to execute the STS motion. A study of influence of chair height on the dynamics of STS motion had been investigated by Schenkman et al.[5] A bilateral active marker-based motion analysis system was used to measure the joint angles and angular velocity. However, the most important issues of dynamics stability and balance for different chair heights had not been covered in their work. The effect of back loading on the kinetics and kinematics of STS motion in healthy children had been determined by Seven et al. [6], in their study. The total duration of STS was not changed to measure the effect of loading. The ankle dorsiflexion during loading was found to be more than that of unloading. The deviation of center of mass of the whole body system had not been reported, which would ensure the stability. A biologically model had been developed for analysis of STS motion by Sibella et al.[7], where the kinematic analysis and kinetics were solved using experimental data. The motions were captured by an optoelectronic system. Further studies are necessary to determine power consumption and balance. Focusing on three major joint motions, namely ankle, knee and hip velocities and assuming the whole body system's linear velocity vector to be function of these three motions, a simple biomechanical model had been developed by Yu et al.[8] in their work. Though kinetics data had not been reported in this work, it was found that ankle-hip motion was critical for the body system's horizontal motion and hip-knee angular motion was primarily responsible for body system's vertical motion. Wang et al.[9] proposed a methodology in order to evaluate the effect of moving track on body loading. Using motion analysis system and force plates, the kinematic data were obtained and those were used as inputs in ADAMS model to determine reaction forces. Then, an optimum control algorithm was used to minimize the cost function. However, the dynamic model was assumed to be very simple and as traditional optimizer was used there was a less chance of getting the globally minima solutions (as mentioned earlier). Another study was conducted by Yamaski et al.[10], where the goal was to minimize jerk of the body's center of mass and change of torque of each joint with respect to time, in order to predict the joint angle trajectory. However, in their study, the traditional optimization technique, namely dynamic programming and variational calculus were used. The ankle was assumed to be fixed with ground, and thus, the model needed to be modified further. For paraplegia patients, it was found that they need to bend their body forward in order to obtain linear momentum of the trunk for comfortable seat-off operation in Jovana et al.'s[11] study. Without considering the studies on power consumption and dynamic balance, this model might not be able to tackle the real case scenario of STS motion of paraplegia patients. There are several existing studies on simulation of STS motion based on single objective genetic algorithm like Yokota et al.'s[12] work. They used improved strength Pareto evolutionary algorithm (SPEA2) to simulate the STS motion. No study on dynamic balance, phase completion time and power consumption had been reported in their work. Moreover, no work has been reported till now on simulation of STS motion using multi-objective optimization by utilizing non-dominated sorting algorithm (NSGA-II). So, there is a need for a detailed analytical modeling, which can closely imitate a real scenario by considering dynamic balance along with different kinematic and dynamic parameters based on suitable optimization technique. The present study is an attempt for simulating human STS motion.

3. Objectives of the present study

In the present study, a 3-dimensional CAD model of the human being is drawn using solid-works. Body mass index and height of an average human being is considered in the model. The aims and objectives of the present study have been set as follows:

- Different ranges of joint angles for ankle, knee, hip and trunk angle are taken to carry out the kinematic study. Lagrangian energy approach is used to formulate the dynamic equations. Zero moment point (ZMP) is calculated and dynamic balance margin (DBM) is constructed.
- An optimization problem is formulated in order to minimize the ankle, knee and hip joint torque and power consumption (with heat loss) with the constraint that ZMP in lateral direction will always fall inside the support foot polygon. To ensure that human body sits on the chair before seat off, a constraint is imposed such that distance of pelvic joint from ground is neither more nor less than the height of the chair. The differences between the maximum, minimum ZMP in forward direction and two extreme margins or points of foot polygon are also minimized to ensure a stable STS motion.
- Multi-objective optimization is carried out to find the minimum power consumption and torque in minimum time as torque and power consumption increases with the decrease in time.

4. Mathematical formulation of the model

The problem has been mathematically formulated as discussed below.

4.1. CAD model

The CAD drawing of sitting posture of human model on a chair along with ground is shown in Figure 1(a). The figure displays all the lower extremity joints of human model sitting on chair. The angles of ankle joint, knee joint, hip joint and pelvic joint are shown in the figure. Since the fingers and foot are always in contact with the ground during STS operation, the finger joints angles (MTP) are always kept at 0^0 with foot. Pelvic angle is the angle made by body trunk or HAT with hip joint.

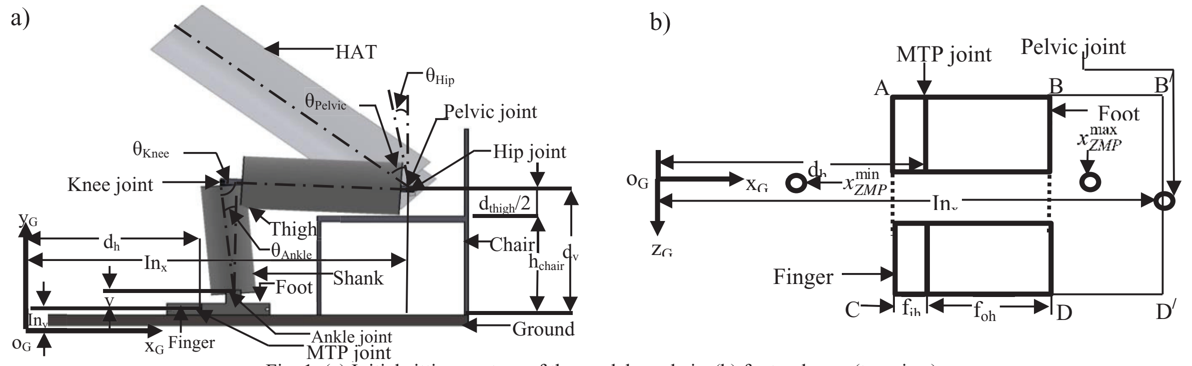

Fig. 1. (a) Initial sitting posture of the model on chair; (b) foot polygon (top view)

A solid-works model of an average adult human has been drawn with a body height of 1795mm (approximately 5ft 10 inches) and body mass index (BMI) of 27.67. So, overall body mass is found to be 89.15 Kg from the BMI, mass and height relationship. The lower limbs of the model consist of thigh, shank, foot and fingers. The head, trunk and arms are assumed to be a single link to make the model simple and they together named as 'HAT'. So, the model consists of nine joints, such as two hip, two knee, two ankle, two MTP (metatarsophalangeal articulations) joints and one pelvic joint. The ratios of individual limb's masses, lengths, center of mass locations from proximal end and radii of gyrations with respect to total body mass, body height and individual segment's length are obtained from Drillis et al.[13] to calculate the individual body part's data as inputs for the dynamic study. HAT, thigh, shank and foot's masses are calculated as 59.16 Kg, 9.52 Kg, 4.02 Kg and 1.44 Kg, lengths are found out to be 835 mm, 500 mm, 380 mm and 272 mm, center of mass distances from proximal end are computed as 414.37 mm, 261 mm, 181.52 mm and 132.90 mm and moment of inertia are given as 680784.57Kg-mm^2, 159554.86 Kg-mm^2, 7189.08 Kg-mm^2 and 12550.33 Kg-mm^2, respectively. In_y is the vertical distance of the MTP joint and In_x is the horizontal distance of pelvic joint from the origin of the global co-ordinate.

4.2. Assumptions of the model

Before carrying out the kinematic and dynamic analyses, some assumptions are made, which are given below.

- The entire STS motion is in bilateral double support phases. Since each of the legs moves in similar way, symmetry in motion analysis is assumed.
- The equal ground reaction forces are applied on feet of both the legs. The dynamic analysis is done by assuming half of the mass and moment of inertia of the HAT to find out torque and power consumption, as bilateral symmetry is presumed.
- The variation of joint angles with time are assumed to follow piecewise cubic spline with 'Not-a-knot' condition, which has a better accuracy to interpolate the intermediate points of a curve rather than other boundary condition.

4.3. Forward kinematics and Inverse Dynamic model

After assigning the coordinates according to Denavit-Hartenberg rules, both the angular and linear displacements, velocities and accelerations of individual limb (kth link) at tth time along x_G and y_G directions are formulated. Then, by using those formulations, the expressions of kinetic $(KE_k(t))$ and potential energy $(PE_k(t))$ are derived for kth link at tth time. Finally, the expression of the torque is obtained, as given in equation (1).

$$\tau_k(t) = \frac{d}{dt}\left(\frac{\partial L_p(t)}{\partial \dot{\theta}_k(t)}\right) - \left(\frac{\partial L_p(t)}{\partial \theta_k(t)}\right), \textit{ where Lagrangian } L_p(t) = \sum_{k=1}^{p}(KE_k(t) - PE_k(t)) \tag{1}$$

So, power consumption of kth link at tth time is determined by taking the derivative of energy terms $(E_k(t))$ with respect to time and is given by equation (2).

$$P_k(t) = \frac{dE_k(t)}{dt} = \tau_k(t)\omega_k(t) + C\tau_k(t)^2, \textit{ where } E_k(t) = \int_o^t (\tau_k(t)\omega_k(t) + C\tau_k(t)^2)dt, \tag{2}$$

where C is a constant term (Nishii et al.[14]), which depends upon the nature of source of heat loss. In the present case, the value is taken as 0.025. The first term in the expression of the energy is ideal power and second term denotes the added external power due to heat loss. The height of upper surface of the chair is considered as h_{chair} and taken as 340 mm. The outer diameter of the thigh in the model is denoted by d_{thigh} and its value is assumed to be equal to 180 mm. Now, the vertical distance (d_v) of pelvic joint from the ground is given by equation (3).

$$d_v = In_y + a_1 \sin(\theta_1) + v\cos(\theta_1) + a_2 \sin(\theta_1 + \theta_2) + a_3 \sin(\theta_1 + \theta_2 + \theta_3) + a_4^c \sin(\theta_1 + \theta_2 + \theta_3 + \theta_4) \tag{3}$$

$$d_h = In_x + a_4^c \cos(\theta_{sum}^{right}) + a_3 \cos(\theta_{sum}^{right} + \theta_5) + a_2 \cos(\theta_{sum}^{right} + \theta_5 + \theta_6) + v\cos(\theta_{sum}) + a_1 \cos(\theta_{sum}) \tag{4}$$

Here, $\theta_1, \theta_2, \theta_3$ and θ_4 are MTP, ankle, knee and hip joint angles with respect to ground, foot (a_1), shank (a_2) and thigh (a_3) of right leg at the initiation of the first phase, respectively. The offset distance between MTP and ankle joints is assumed to be 'v'. a_4^c is the centre of mass distance of the pelvic joint form hip joint. In order to formulate dynamic equations, the MTP joint of the right leg of the assumed model is considered to be starting link. However, the STS motion will be started by keeping pelvic joint fixed with chair. To calculate the horizontal and vertical linear displacement with respect to pelvic joint, first horizontal distance of the pelvic joint (In_x) from global coordinate is to be found out and then, the horizontal distance of the MTP joint (d_h) of the left leg from global coordinate is determined. Then, from the bilateral symmetry of the two legs, the horizontal linear displacement of right leg is calculated to be the same as that of left leg. The expression of the MTP joint distance (d_h) from global coordinate is given by equation (4). Since, the linear and angular displacements of all limbs of the model are calculated starting from that of MTP joint of right leg, the displacements of the left leg of the model is also actually determined with respect to right leg. This is the reason for which equation (4) is based on the hip (θ_5), knee (θ_6), ankle (θ_7) joint angles of left leg and pelvic joint angle with respect to MTP joint $\theta_{sum} = \theta_1 + \theta_2 + \theta_3 + \theta_4$ of right leg. Here, $\theta_{sum} = \theta_{sum}^{right} + \theta_5 + \theta_6 + \theta_7$.

4.4. Zero moment point (ZMP) and dynamic balance margin (DBM)

Figure 1(b) displays the top view of the feet along with the fingers of both legs. The length of fingers and foot is denoted by fi_h and fo_h, respectively. The zero moment point of a system can be defined as the point about which the moments of all reaction forces become equal to zero. There is sufficient friction between the lower surface of foot and upper surface of ground, which can hold the human body without slipping during the operation. Since both the legs are in contact with the ground, the foot polygon can be defined as ABCD. Both of the zero moment points in x and z-directions must be fall within the margin of ABCD in order to maintain dynamic balance during STS motion. The expression of the ZMPs in horizontal $(x_{ZMP}(t))$ and vertical directions $(z_{ZMP}(t))$ is given by equation (5) at t[th] time.

$$A_{ZMP}(t) = \frac{\sum_{k=1}^{p} (I_k \omega_k(t) + m_k A_k(t)(\ddot{y}_k(t) - g) - m_k \ddot{A}_k(t) y_k(t))}{\sum_{k=1}^{p} m_k(\ddot{y}_k(t) - g)}, \quad A = \text{either } x \text{ or } z \tag{5}$$

5. Formulations of the optimization problem

In the present study, four phases are considered from seating posture to standing. Each phase is defined by its completion time and joint angle. The aim of this study is to find out the total time during which the model can stand comfortably with minimum torque and power consumption provided the dynamic balance is maintained. Now, there are four joints, namely ankle, knee, hip and pelvic joints. There are five different control points, as there are four phases. Now, the piecewise cubic spline must be drawn through these control points to get the joint angle trajectories with respect to time. Now, apart from final positions of standing straight (when the joint angles will be closed to 0^0), the values of joint angles are unknown at intermediate times and a genetic algorithm (GA) is used to find this joint angles. Due to robust search capability of finding globally optimum solution, a real-coded genetic algorithm (RGA[15]) is used. The single objective optimization problem is formulated as follows:

$$Minimize: 0.20 \times (P_{ankle}^{max} + P_{knee}^{max} + P_{hip}^{max} + \left| x_{ZMP}^{max} - (d_h + fo_h) \right| + \left| x_{ZMP}^{min} - (d_h - fi_h) \right|)$$

subject to $z_{ZMP}(t)$ lies within ABCD; $(\left| d_v - (h_{chair} + 0.5 \times d_{thigh}) < H_c \right|)$

and

$$(90^0 < \theta_{ankle} < 130^0), (-120^0 < \theta_{knee} < 0^0), (0^0 < \theta_{hip} < 100^0), (0^0 < \theta_{pelvic} < 45^0), (0 < t_{interval} < 1)$$

The objective function consists of five terms. The first three terms are the maximum values of ankle (P^{max}_{ankle}), knee (P^{max}_{knee}), and hip (P^{max}_{hipe}) joints' power consumption that are obtained during the overall time duration to complete the task of STS motion. From Figure 1(b), it is shown that initially the foot polygon has been surrounded by boundaries $AB^{/}$, $B^{/}D^{/}$, $D^{/}$ C and CA, and thus, constitutes a rectangle $AB^{/}D^{/}C$. Theoretically, the polygon must be shifted instantaneously to rectangle ABCD, as the model starts to stand from initial sitting condition from chair to maintain balance. However, in real scenario, the zero moment point needs some time to fall within ABCD instead of falling momentarily. The genetic algorithm starts with some initial population of solutions, which are the random values of the design variables chosen from their respective ranges. So, for a chosen combination of values of the operating variables, there may be the case when the zero moment point in x-direction can fall outside the foot polygon ABCD. The points which falls left of the side AC of the foot polygon ABCD, can be expressed by $(d_h\text{-}fi_h)$ and the points which falls right side of the side BD can be denoted by (d_h+fo_h). The case, when the maximum (x^{max}_{ZMP}) and minimum (x^{min}_{ZMP}) values of zero moment point along x-direction fall outside of the foot polygon ABCD (left and right of side AC and BD) is shown in Figure 1(b). In this case, to ensure balance along forward direction (x-direction), the absolute values of the differences of maximum and minimum values of zero moment points (during the total operation time) from the points lying outside ABCD is also minimized, which leads to adding the fourth and fifth terms along with previous three terms. The weight values associated with these terms are assumed in such way that each of them contributes equally in the minimization problem and thus, taken as 0.20. The zero moment point in z-direction must not cross the boundary of foot polygon ABCD, which is ensured by the first constraint. Here, H_c is a constant, which is used to ensure initial seating posture on chair, as there must not be any gap between upper surface of chair and lower face of thigh. So, ideally, this value should be equal to 0. There are five control points of the four phases. Each of the joint angles is varied with time through these control points. Now, the ordinate value of the final control points of each of these joint angles are known, as the values of these become either 0^0 or 90^0 or 180^0 (depend upon reference point) in case of standing straight on ground (final phase). The value of the abscissa of the first control point is 0, as abscissa indicates value of starting time which always starts from '0'. So, there are 20 variables, among which 16 variables denote the ordinate values of four control point (excluding the last one), which are the four joint angles and four variables denote the abscissas of four control point (except the first one) which are the values of time interval ($t_{interval}$) of each phase (P_1,P_2,P_3,P_4) of the STS motion. Now, keeping the same geometric and functional constraints, a multi-objective optimization problem is formulated and solved by using multi-objective genetic algorithm (NSGA-II[16]) to minimize both total time (t_{total}) to complete STS operation and power consumptions required at three different joints along with the difference of maximum and minimum value of zero moment point in x-direction from the point lying outside the foot polygon ABCD. So, the constrained multi-objective optimization problem can be formulated as follows:

$$Minimize: 0.20\times\left(P^{max}_{ankle}+P^{max}_{knee}+P^{max}_{hip}+\left|x^{max}_{ZMP}-(d_h+fo_h)\right|+\left|x^{min}_{ZMP}-(d_h-fi_h)\right|\right)$$

and

$$Minimize: t_{total}$$

subject to $z_{ZMP}(t)$ lies within ABCD; $\left(\left|d_v-(h_{chair}+0.5\times d_{thigh}) < H_c\right|\right)$

and

$$(90^0<\theta_{ankle}<130^0),(-120^0<\theta_{knee}<0^0),(0^0<\theta_{hip}<100^0),(0^0<\theta_{pelvic}<45^0),(0<t_{interval}<1)$$

6. Results and discussion

Results of the single objective and multi-objective optimization problems are stated and discussed below.

6.1. Single objective optimization

As the performance of a GA depends on its parameters, namely probability of crossover (P_c), mutation probability (P_m), population size (N) and maximum number of generations (G_{max}), a thorough parametric study is conducted. The ranges of P_c, P_m, N and G_{max} are assumed to be (0.5-1), (0.001-0.011), (200-600) and (100-500), respectively. Now, each parameter is varied within its range keeping other parameters fixed at their corresponding mid-values. By following this procedure, the values of the optimum parameters are obtained as 0.5, 0.01, 400 and 500. The value of the objective function is found as 124.077356 for the set of optimum parameters. The values of simulated binary crossover (SBX) and polynomial mutation (σ) operators are taken as 2 and 4, respectively. Now, the variations of different joint angles (corresponding to optimal solution for the design variables) against time are shown in Figure 2(a), and the CAD model (Solid-works) of different phases of STS motion are displayed in Figure 2(b). The variations of joint angles shown in Figure 2(a) indicate that ankle joint starts with a dorsiflexion of 7^0 and then starts to dorsiflex further up to 37^0, followed by plantar flexion to neutral position at termination phase (during standing). The body load is transferred through the foot via ankle joint and due to the forward motion of the trunk and whole body, there is a certain dorsiflexion required to make the forward motion (from initial siting to end of first phase) more stable. Then, plantar flexion starts from phase 3 and continues to phase 4. There is a gradual extension of knee joint angle from initial phase (80.62^0) to final standing phase (180^0). Hip joint starts from a flexion of 10^0, followed by a gradual extension to 0^0 during phase 4. Similar type of curves denoting the variations of knee and hip joint angle against time can be observed in Yamaski et al.[10]. There is a requirement of initial lifting of the HAT and waist, at the time to start STS motion in order to be contactless with chair and the 10^0 flexion make this easier. Pelvic joint starts with a forward angle of 45^0 and ends with 0^0 at terminal phase. There is certain rise and drop in the variations of pelvic joint angle, which may be due to the continuous effort to establish the balance. By using the values of joint angles at different time duration, as inputs to dynamic simulation package (ADAMS), the simulation of STS motion is modelled (shown in Figure 2(b)). In Figure 3(a), the joint torque and power consumption values are plotted against the time required to complete the different phases. From Figure 3(a), it is observed that the ankle joint torque reaches to its peak value (70.22 N-m) in between phases 1 and 2. Initially, the foot and thigh are in contact with the ground and chair, respectively, and in order to stand there is sudden change from initial contact to contactless condition, which transfers a sudden load to the ground via ankle joint. This explains high starting torque required to initiate the phase1 (try to rise) with a value of 35 N-m approximately. There are certain peaks and valleys in the variation due to dorsiflexion and plantar flexion and because of this reason the required torque (to complete the motion) reaches to local maximum and minimum before each motion reversal. The nature of this curve approximately agrees with the work of Błażkiewicz et al.[17].

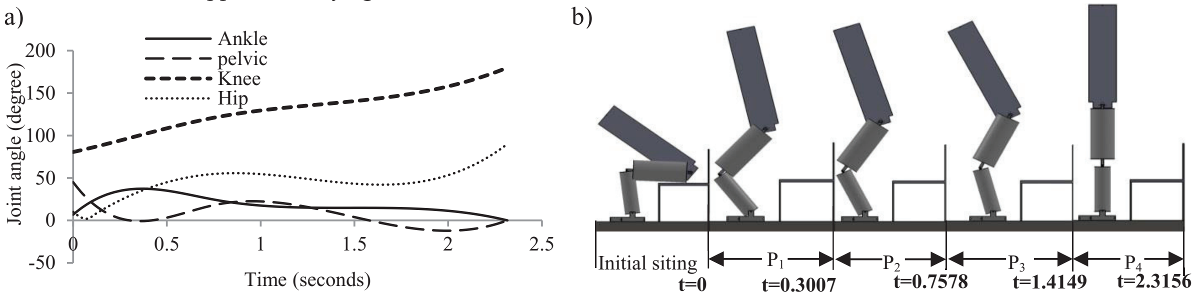

Fig. 2. (a) Variations of joint angles against time; (b) CAD model of the phases of sit-to-stand motion

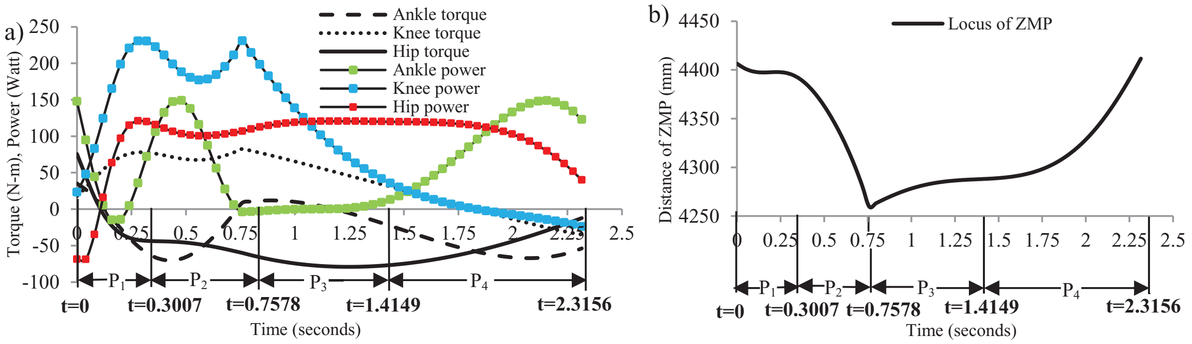

Fig. 3. (a) Variations of joint torque and power consumption against time; (b) Distance of Zero Moment Point from global co-ordinate

The peak value of knee joint torque is found to be 82.60 N-m (the highest one among three values of joints torques). The required torque to move shank (knee joint) at the beginning of the phase is less (17.84 N-m) unlike ankle joint and then, gradually increases up to peak value at the end of phase 2. Since the knee joint has more contribution to move different limbs up to phase 2, the required torque becomes the highest during this phase. Then, there is a steep decrease in the knee joint torque and termination phase is ended with a lower value with a change of direction (negative due to motion reversal). Starting hip joint torque is found to be equal to75.6 N-m. Peak hip torque (-79 N-m) is reached at almost the end of phase 3. The similar trends can be observed in the hip and knee joint moment curves against time in Yoshioka et al. [18]. The variation of power consumption for ankle joint is the mirror image of joint torque curve during peak and valley, as there are repeated motion reversals (dorsiflexion to plantar flexion), for which angular velocity becomes negative and subsequently, the power consumption becomes positive (after multiplying with negative value of torque). The maximum value of ankle joint power consumption is obtained as 148.78 watt at the same time, when ankle joint torque takes its maximum value (between phases 1 and 2). The similar trend is observed in case of variation of power consumption of hip joint and the maximum power consumption is found to be equal to 120.55 Watt, at the same time when the maximum hip joint torque is observed. The nature of power consumption curve is same as that of knee joint torque, as there is no motion reversal. Similarly, the highest value of power consumption at knee joint is found out to be equal to 230.64 Watt and this is the highest joint power consumption obtained among the three joints likewise the case of joint torque. In Figure 3(b), the locus of zero moment point is shown with respect to global co-ordinate system. The x-coordinate values of the MTP joints are found to be 4225.58 mm from the origin (o_G) of the global co-ordinate system. So, the ranges of foot polygon are calculated to be (4139.58 mm, 4411.58mm) by subtracting and adding the values of lengths of finger (86 mm) and foot (186 mm), respectively. Now from Figure 3(b), it is observed that the maximum and minimum values of x-coordinate of ZMP (x_{ZMP}) are 4411.61 mm and 4259.65 mm at the end of termination phase. It indicates that the zero moment point remains in foot polygon during entire STS motion, which confirms the dynamic balance. The joint torque values are also calculated in the dynamic simulation software. The average absolute percentage deviations of ankle, knee and hip joint torques calculated through inverse dynamics from that of simulations are 0.076%, 0.035% and 0.037%, respectively.

6.2. Multi-objective optimization

Using the same ranges of GA parameters and by following the same procedure for parametric study, the following optimal parameters are obtained: P_c=1, P_m=0.003, N=600 and G_{max}=500. Figure 4 shows the Pareto-optimal front of solutions. If someone wants to stand from sitting condition within a time as less as possible, the angular velocity and acceleration of individual limb will increase, which causes a subsequent increase of torque and power consumption required to move the body parts and different joint. This explains the self-contradicting nature of the curve in Figure 4. Figures 5(a) and (b) show the variations of joint angles with time and CAD model of the STS motion, respectively.

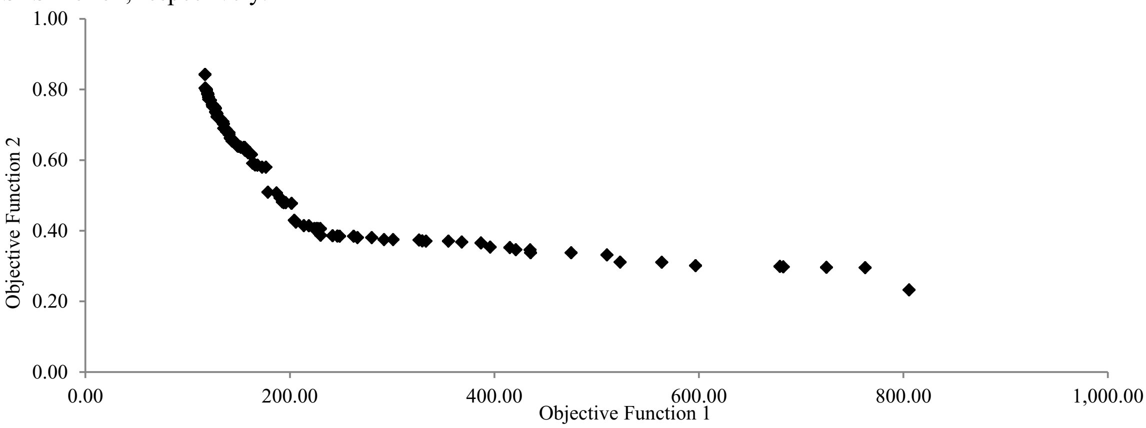

Fig. 4. Pareto-optimal front of solutions

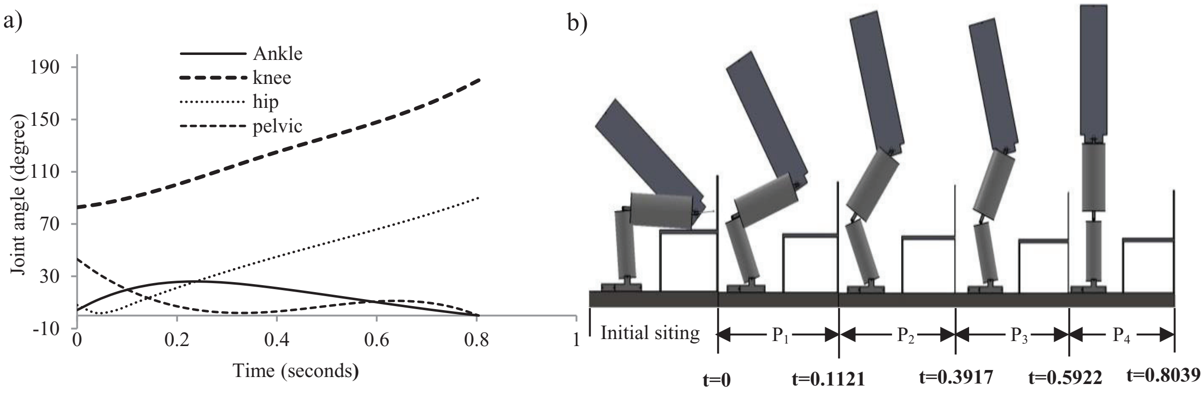

Fig. 5. (a) Variation of joint angles against time; (b) CAD model of the phases of sit-to-stand motion

In case of multi-objective optimization, where the STS motion is to be completed in minimum time with minimum torque, the required torque to move ankle is started from a low value (-11 N-m) and gradually increases to 79.18 N-m at the end of phase 4 (shown in Figure 6(a)). The values of angular and linear velocity and acceleration are high, as the whole motion is completed in less time, which causes more amount of joint torque to move the limbs. The peak value of knee joint torque is found to be equal to 56.90 N-m. The required torque to move shank (knee joint) at the beginning of the phase is less (17.84 N-m) unlike ankle joint and then, gradually increases up to peak value at the end of phase 2. In case of multi-objective optimization problem, the values of knee joint torque are comparatively lower than ankle joint torque unlike for the case of single objective optimization, where the maximum knee joint torque is more than that of ankle joint torque. It may be due to the fact that as less time is available for transferring load through foot via ankle joint, the maximum load is carried by ankle joint, which reduces the contribution of knee joint in order to complete STS motion. A gradually decreasing nature is observed in the curve of hip joint torque against time, where its peak value (77.8 N-m) is observed from beginning of the phase 1. The maximum values of power consumptions for ankle, knee and hip joints are found to be 100.55 Watt, 197.21 Watt and 197.65 Watt, respectively. The average percentage deviation of the joint torques calculated by simulation and inverse dynamics are found to be equal to 4.41%, 0.37% and 0.5 %, for the ankle, knee and hip joints, respectively. In Figure 6(b), the locus of zero moment point is shown. The dimensions of foot polygon are calculated to be (4122.64 mm, 4394.64 mm). It is observed that the maximum values of locus zero moment point in x-direction (x_{ZMP}) is obtained as 4454.54 mm, which is outside the foot polygon zone. After the middle of phase 2, the zero moment point falls inside the foot polygon. Since the time duration for each of the phase is less, the trunk and whole body need certain time to adjust themselves in order to maintain the dynamic balance.

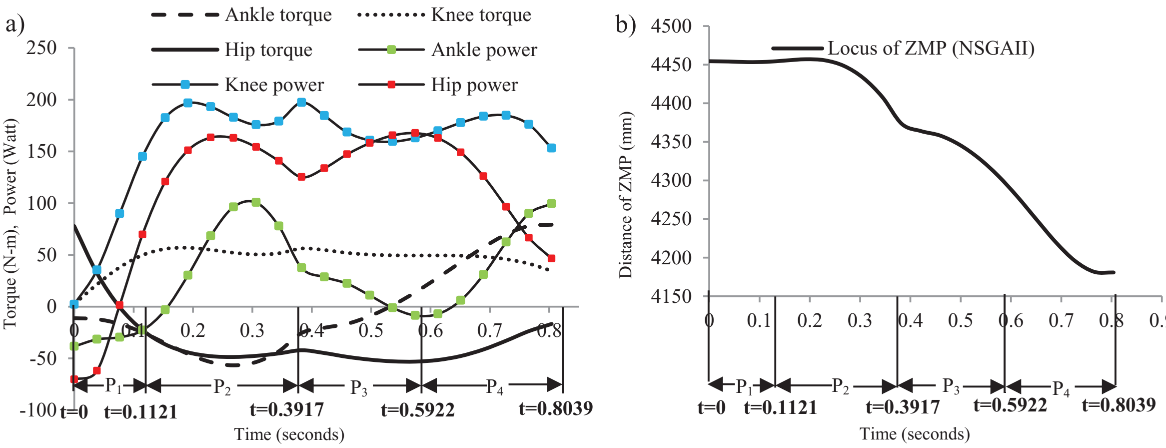

Fig. 6. (a) Variation of Joint torque and power consumption against time; (b) Distance of Zero Moment Point from global co-ordinate

7. Conclusion

The GA is able to solve the optimization problem successfully. From the results of single objective optimization problem, the maximum value of joint torque is found to occur at knee, which matches with general experience of a human-being during his/her STS motion. In case of two-objective optimization, Pareto-optimal front of solutions has been obtained, from which it is possible to determine the amount of torque or power required to complete the STS motion in a predetermined time. Thus, the GA has shown its ability to evolve optimal strategies to solve STS motion. This study will facilitate the design of different assistive devices (orthotic and prosthetic devices) without carrying out rigorous experiments. Though the model is able to generate an approximate data bank for kinematic and dynamic studies, there are certain limitations, which are as follows: The model can be modified more close to a real scenario by considering an accurate model of ground reaction force. The number of phases considered in the model can be varied to get the optimum number of phases. The real experiments are yet to be carried out validate the results. The fatigue degree of real persons will also be examined in future.

References

1. Kamaruddin MK, Arif NM, Salim MS. Sit to Stand Motion Analysis Based on Body Mass Index. In: *In proceedings of the IEEE EMBS International Conference on Biomedical Engineering and Sciences*. 2012, p. 149-152.

2. Millington PJ, Myklebust BM, Shambes GM. Biomechanical analysis of the sit-to-stand motion in elderly persons. *Archives of Physical Medicine and Rehabilitation 1992;* **73**(7):609-617.

3. Mombaur K. Optimization of sit to stand motions of elderly people for the design and control of physical assistive devices. *Special Issue: 85th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM)* 2014; **14(1)**:805-806.

4. An Q, Ishikawa Y, Nakagawa J, Oka H, Yamakawa H, Yamashita A, Asama H. Analysis of Contribution of Muscle Synergies on Sit-to-Stand Motion Using Musculoskeletal Model. *IEEE Workshop on Advanced Robotics and its Social Impacts*. 2013, p. 13-18.

5. Schenkman M, Riley PO, Pieper C. Sit to stand from progressively lower seat heights - alterations in angular velocity. *Clinical Biomechanics* 1996; **11**(13); 153-158.

6. Seven YB, Akalan NE, Yucesoy CA. Effects of back loading on the biomechanics of sit-to-stand motion in healthy children. *Human Movement Science* 2008; **27**: 65–79.

7. Sibella F, Galli M, Romei M, Montesano A, Crivellini M. Biomechanical analysis of sit-to-stand movement in normal and obese subjects. *Clinical Biomechanics* 2003; **18**; 745-750.

8. Yu B, Holly-Crichlow N, Brichta P, Reeves GR, Zablotny CM, Nawoczenski DA. The effects of the lower extremity joint motions on the total body motion in sit-to-stand movement. *Clinical Biomechanics* 2000; **15**: 449-455.

9. Wang FC, Yu CH, Lin YL, Tsai CE. Optimization of the Sit-to-Stand Motion. In: *In proceedings of the IEEE/ICME International Conference on Complex Medical Engineering*. 2007, p. 1248-1253.

10. Yamasaki HR, Kambara H, Koike Y. Dynamic Optimization of the Sit-to-Stand Movement. *Journal of Applied Biomechanics* 2011; **27**:306-313.

11. Jovana J, Christine AC, Philippe F, Vincent B, Charles F. Optimization of FES-assisted rising motion in individuals with paraplegia. BIO Web *Conference*. 2011.

12.Yokota H, Ohshima S, Mizuno N. Sit to stand Motion Analysis using multi-objective Genetic Algorithm Based on Musculoskeletal Model simulation . IEEE Journal of Industry Applications 2015; **5(3)**: 236-244

13. Drillis R, Contini R. Body Segment Parameters. New York, New York: Office of Vocational Rehabilitation; 1966. Report No.: No. 1166-03.

14. Nishii J, Ogawa K, Suzuki R. The optimal gait pattern in hexapods based on energetic efficiency. In: *In proceedings* of 3rd *International* Symposium on Artificial life and Robotics. 1998, p. 106- 109.

15. Deb K, Kumar A. Real-coded Genetic Algorithms with Simulated Binary Crossover: Studies on Multimodal and Multi-objective Problems. Complex Systems 1995; **9**: 431-454.

16. Deb K, Pratap A, Agarwal S, Meyarivan T. A Fast and Elitist Multi-objective Genetic Algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation* 2002; **6(2)**:182-197.

17. Błażkiewicz M, Wiszomirska I, Wit A. A New Method of Determination of Phases and Symmetry in Stand-To-Sit-To-Stand Movement. *International Journal of Occupational Medicine and Environmental Health* 2014; **27(4)**:660–671.

18. Yoshioka S, Nagano A, Hay DC, Fukashiro S. Peak hip and knee joint moments during a sit-to-stand movement are invariant to the change of seat height within the range of low to normal seat height. *Biomed Eng Online* 2014; 13: 27.