Hip 3D Joint Mechanics Analysis of Normal and Obese Individuals' Gait

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Abstract— **Previously, the study of 3D joint angle has been proven to give better interpretations on the joint and muscular activities. However, it has not been widely discovered and usually limited to normal subject and level walking activity. The inspiration of the study was based on the fact that, the obesity and staircase activity factors will significantly influence the mechanics of a joint. It has been proven significantly affected the knee rather than the hip which leading to the knee osteoarthritis disease. Moreover, since to date no experimental study has reported on hip 3D joint mechanics associating with these two factors, therefore, the analysis of hip 3D joint angle for obese and normal individuals during stair ascending activity have been proposed in order to help the hip 3D joint interpretations. Our hypothesis is that, it is hard to describe the difference of the gait strategy used between obese and normal individuals due to the effect of the mechanics adaptations of the hip joint. Therefore, with the aid of hip 3D joint angle interpretations, it is believed that these phenomena can be successfully described and investigated. The result seems to confirm that, at the late stance of stair ascending activity, the obese individuals seem to have an alternative strategy of mainly hip resistance compared to the normal' strategy of mainly hip stabilization. Otherwise, the normal and obese individuals seem to have a similar strategy of mainly hip stabilization. In addition, the obese seem to absorb or generate energy with systematically lower proportion of the 3D joint moments than normal individuals.**

Keywords— **3D joint angle, 3D joint power, inverse dynamics, Euler/Cardanic angle, stair ascending.**

I. INTRODUCTION

3D joint moments, angle and joint power vectors have initially been used to investigate the gait strategy used in normal adult's and children's gait [1][2]. However, the discovery pertaining to this issue is still new and most of the time the research is focused on normal subjects and during level walking activity. Thus, the area of the research seems can be expanded to the other form of motion activities and involve with obese community which believed associated with a large number of loads cycle [3].

Theoretically, the joint power is the best method to appropriately describe the muscle activities whether it is negative, null or positive joint power which corresponds to an absorbed, null or generated energy coarsely associated to eccentric, isometric or concentric muscular actions [4]. However, when stand alone it seems insufficient to give details explanation on the joint and muscular activities. Therefore, the introduction of 3D joint angle is purposely to help the 3D joint power interpretations in a manner of describing the proportion of the joint moment which contributes to the movements (i.e. propels, resists or stabilized the joint). Moreover, with the aid of inverse dynamics approach, the calculations are become simpler without the need of musculo-skeletal modeling as been required in the forward dynamics analysis.

The focused of the study was to analyze the hip 3D joint mechanics for obese and normal individuals during stair ascending activity. It could be used to investigate the gait strategy used and how the neuromuscular adaptations applied to the joint. It is of interest due its vast contributions in understanding the mechanics of normal and pathology of the hip joint during normal and abnormal loading conditions [5]. Besides the human hip joint can withstands peak contact forces up to 4 to 5 times of the body weight [6][7][8], however, the repetition of high joint loading profile will make it more susceptible to injury and structural deterioration over time and this situations can be worsen when involving with obese individuals.

In the present study, the selection of stair ascending rather than stair descending activity was made based on the judgment that, even both hip joint contact forces and moments are significantly higher for stair descending than for stair ascending activity, however, the effective contact areas of the stair ascending are relatively small in comparison to descending stair activity which lead to the high pressure distribution at the hip joint acetabulum (even with a small value of joint contact forces) [6][9]. In addition, for obese individuals, this task is quite demanding where the motor functions are reduced [10]. Besides, this task is comparably much more important than level walking activity due to during level walking activity the hip joint angular velocity remains relatively small and passive resistance of the skeleton to the gravity is considerably less than one times of the body weight [7].

Human body automatically has been programmed to adapt to the outside environment for the sake of the skeletal health of the joint. For obese individuals, the compensatory mechanism relative to their BMI (body mass

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index) including slower walking speed, shorter stride length, increased double support phase and decreased knee range of motion are the true examples of the kinematics adaptations of human locomotion [6][11][12][13]. This phenomena are associated with an adaptation to minimize metabolic energy expended per unit distance traveled [8], to reduce peak pressure distributions [5], to offset total inertia generated [14][15] and above all to reduce muscle forces and moment [11][16][17][18]. Therefore, at the end of the day it is believed that this study will give different perspectives in describing the mechanics adaptations of a body in reaction to internal and external mechanical changes.

In this context, the hypothesis is that, it is hard to describe the difference of the gait strategy used between the obese and normal individuals due to the effect of the mechanics adaptations of the joint. Therefore, with the help of 3D joint angle interpretations, it is believed that, at the end of the day these phenomena can be successfully described and investigated.

II. MATERIALS AND METHODS

A. Gait Experimental Protocol

10 healthy normal male subjects, 10 healthy obese male subjects, 10 healthy female subjects, and 10 obese female subjects without any history of lower limb participated in this experiment. The normal subjects had average age, height, weight and BMI of 23.4 ± 2.26 years old, 1.6 ± 0.09 m, 58.45 ± 7.65kg and 22.37 ± 1.38 kg/m^2, respectively. While the obese subjects had average age, height, weight and BMI of 23.65 ± 2.21 years old, 1.62 ± 0.08m, 84.88 ± 9.36kg and 32.17 ± 1.46kg/m^2, respectively**.** The normal and obese groups were matched by their BMI according to World Health Organization standard. The subjects were classified as a normal subject for the BMI range of 18.5 to 24.9 kg/m^2, and they were classified as an obese subject for the BMI range of 30 to 34.9 kg/m^2.The subjects were provided informed consent in accordance with the policies of University of Malaya's Ethical Committee. All participants above all must complete a medical history questionnaire and they must indicate whether they have no current or past neurological or cardiovascular disorders, orthopedic abnormalities or pain, were never diagnosed with arthritis in any joints, were not diabetic and no other health problems, must be remarkably fit in all other aspects and they could walk without difficulty or pain.

Twenty anthropometric parameters were taken for each of the subjects in order to calculate the body segment parameters will be finally be used in the inverse dynamics analysis [19][20]. Sixteen passive reflective markers were carefully stuck on subject's lower limbs bony landmarks based on the VICON Skeleton Template for the basic lower body model in order to prevent underestimation of the prediction of the hip joint centre position and motion artifact due to the variability of the subjects' BMI [2][21][22][23]. The subject then asked to climb a custom-made three-step stair with standard dimensions of 17cm riser and 29cm tread (Figure 1) as proposed for the design of the stairs in public environments [6].

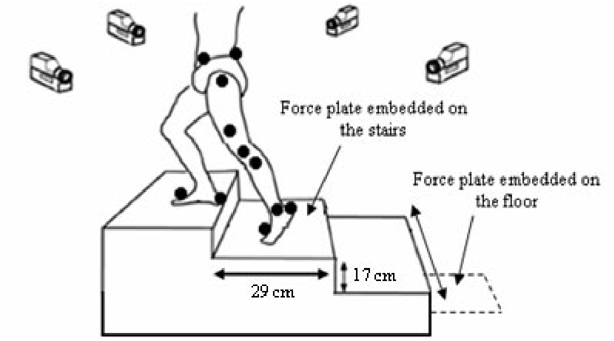

Fig. 1 Schematic diagram showing a subject ascending a three-step stair with tested foot step on the second step fitted with force platform

Prior to the experiment, the subject was asked to walk through the experimental area until he/she felt relaxed and comfortable. Each of the experimental condition was measured five times. 3D motion trajectories data of the markers were recorded with sampling rate of 50Hz using seven-camera VICON Nexus motion analysis system. The ground reaction forces and moments were measured simultaneously at sampling rate of 200Hz using one Kistler Force Plate and one AMTI force plate. The force plates were arranged as shown in the figure 2. A starting point was selected so that the right foot will contact the force platform in a normal stride. A trial was discarded if the foot was not completely step on the force platform or if the subject made visually obvious stride alterations to contact the force platform.

B. Data Processing

All markers' trajectories data were filtered in order to remove unwanted signals due to markers vibrations or motion artifacts. The filling gap processed were also implemented in order to predict the actual positions of the markers locations in which the VICON system fail to capture the actual markers positions due to its invisibility during recording processed. The trials were examined in order to get the clearest markers positions and to ensure the consistency of the gait patterns. The bad representation of the trial was omitted.

After signal processing, the computations of body segment parameters, joint centre positions, linear velocity and acceleration of segment's COG, and segment angular velocity and acceleration data were executed first before the calculations of the joint forces, moments, power and angle could be proceed. The body segment parameters were calculated through the multiple regression equations [19][20]. The hip joint centre was predicted based on the external body landmarks, 3D markers positions and prediction equations [19]. The linear velocity and acceleration of the segment's COG were computed by their first and second derivatives of displacement-time data, whereas the angular velocity and acceleration were computed by their first and second derivatives of displacement-cardanic angles data. The first and second derivatives of the linear and angular components were calculated based on the finite difference methods derived from Taylor series expansions [24]. All the calculations were implemented in MATLAB 2008.

The joint forces and moments were computed successively, respectively in the global reference frame and segment reference frame by means of bottom up inverse dynamics approach based on vectors and Cardanic angles. Then, the hip 3D joint moments were re-sampled on 60% of gait cycle and normalize to dimensionless value [2]:

$$M_{normalize} = \left(\frac{M}{m_0 L_0 g} \right) \tag{1}$$

where m_0 is the body mass, L_0 the lower limb length and g the gravity acceleration. After that, the 3D joint angle was computed [1, 2]:

$$\alpha_{M\omega} = \tan^{-1} \left(\frac{\|M \times \omega\|}{M \bullet \omega} \right) \tag{2}$$

and re-sampled on 60% of the gait cycle. Therefore, it was defined positive in the range of 0° to 180° [1]. The equation (2) above is directly related to 3D joint power by:

$$P = \|M\| \|\omega\| \cos \alpha_{M\omega} \tag{3}$$

The joint power was then re-sampled on 60% of the gait cycle and normalized to dimensionless value, P_0 [25]:

$$P_0 = \left(\frac{M \bullet \omega}{m_0 \sqrt{g^2 L_0^{\,3}}} \right) \tag{4}$$

The interpretation of the 3D joint angle and its correlation to the 3D joint power is described as [1][2]: (1) when the 3D angle is in the interval of 0° to 60°, the joint is assumed principally in the propulsion configuration, (2) when the 3D angle is in the interval 60° to 120°, the joint is considered principally in the stabilization configuration (3) when the 3D angle is in the 120° to 180°, the joint is considered principally in the resistance configuration.

It this experiment, the evaluation of the gait was performed only at the stance phase or 60% of the gait cycle. This was because at swing phase (61% to 100% of the gait cycle), the hip joint power and moments tend to zero where extra cautions were necessary when analyzing this phase [2]. While, the introduction of dimensionless value was to ensure that there was unnecessary for normalization or scaling procedure [2][25][26] .

III. RESULT

A. *Hip 3D Joint Moments*

The hip 3D joint moments (Figure 2(a)-(c)) reveal approximately similar curve patterns between normal and obese individuals. However, normal individuals never show flexion and external moments in comparison to obese individuals where the durations are 10% and 26% of the gait cycle, respectively. Considering the entire stance, the standard deviation is more important for normal than for obese individuals at internal/external and abduction/adduction. Besides, the dimensionless extension (-0.4736 and -0.3514 dimensionless for obese and normal, respectively), internal (0.2607 and 0.1376 dimensionless for obese and normal, respectively) and abduction (0.1483 and 0.0219 dimensionless for obese and normal, respectively) moments were significantly superior for obese individuals at pre-swing.

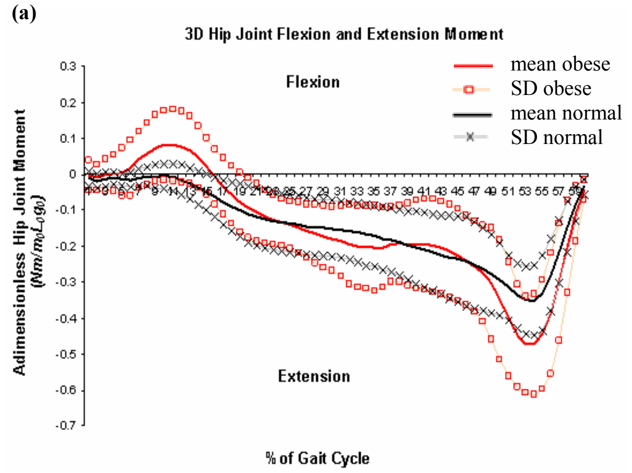

Fig. 2 (a), (b) and (c) Mean hip 3D joint moments (±SD) dimensionless on 60% of the gait cycle about flexion-extension, internal-external and abduction-abduction rotation axes, respectively

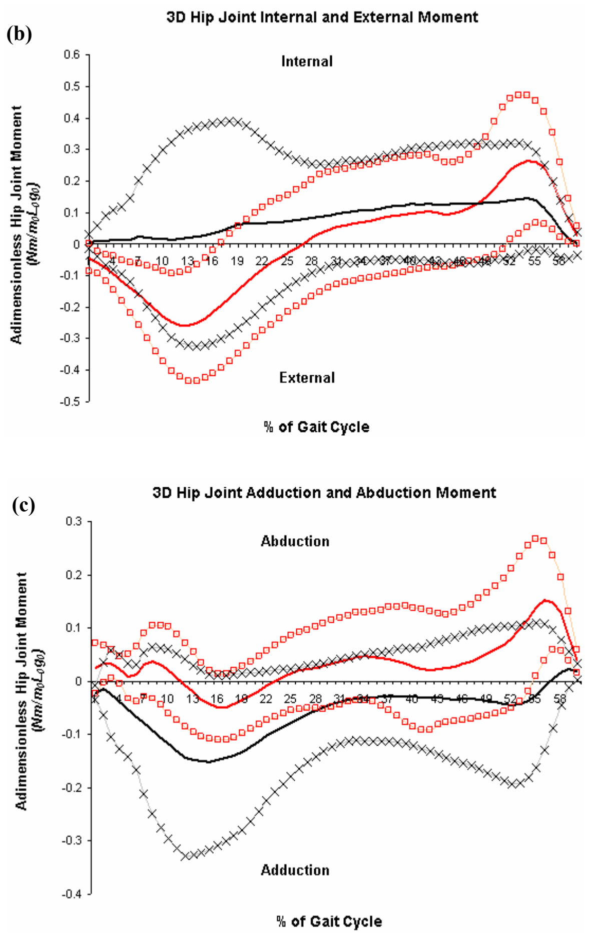

Fig. 2 (*continued*)

B. Hip 3D Joint Power

The hip 3D joint power (Figure 3) shows variability in the configuration of absorbed, null and generated energy with both normal and obese individuals show approximately similar curve patterns. However, for normal individuals, the configuration of generated energy can be shortly observed (6% of the gait cycle) at late stance. Considering the entire stance phase of gait cycle, the configuration of absorbed energy is significantly longer for normal (29% of the gait cycle) than for obese individuals (19% of the gait cycle). Peaks 3D joint power is always superior for obese at mid-stance (-0.4078 dimensionless) and at pre-swing (-0.3237 dimensionless) with the obese individuals significantly absorbed more energy than normal individuals. However, both subjects tend to produce low or null energy at 25% to 52% of the gait cycle.

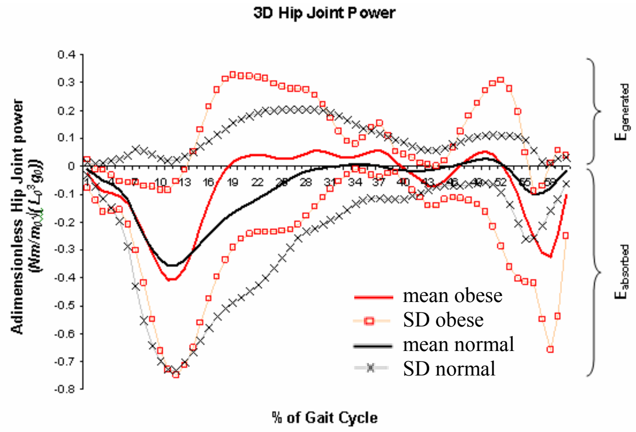

Fig. 3 Mean hip 3D joint power (±SD) dimensionless on 60% of the gait cycle

C. Hip 3D Joint Angle

The hip 3D joint angle (Figure 4) for normal and obese individuals approximately depicts similar curve patterns which exclusively reveal mainly a stabilization configuration by dominating 42% and 48% of the gait cycle for obese and normal individuals, respectively. Both subjects never show a propulsion configuration for the entire stance. However, peak hip 3D joint angle is slightly higher and shorter (150^0 or 86.6% of the hip 3D joint moments contribute to the joint power) for normal than for obese (140^0 or 76.6% of the hip 3D joint moments contribute to the joint power) at early stance. Besides, two different joint configurations of resistance and stabilization exist at late stance phase for obese and normal individuals, respectively. Moreover, for the first 30% of the gait cycle, 3D joint angle is slightly lower for obese than for normal individuals and vice versa for the last 30% of the gait cycle.

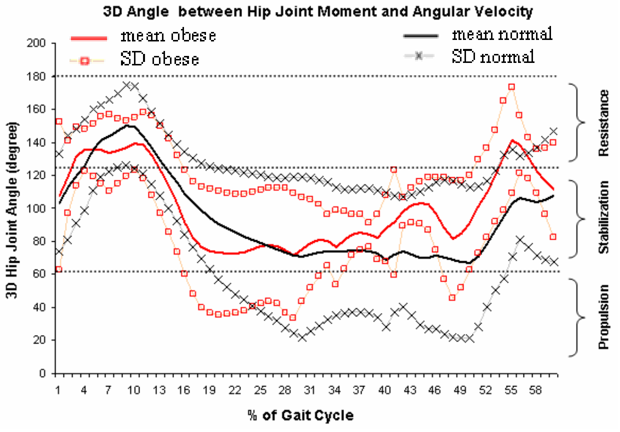

Fig. 4 Mean hip 3D joint angle (±SD) dimensionless on 60% of the gait cycle

IV. DISCUSSION

The 3D joint dynamics showed variability at initial stance and late double stance phase for both obese and normal individuals. At initial stance, obese individuals tend to flex, external rotate and abduct the hip joint, whereas normal individuals tend to extend, internal rotate and adduct the hip joint. These configurations were associated with a high absorbed energy confirmed by a resistance configuration with 76.6% and 86.6% of the joint moment contributing to the joint power for obese and normal individuals, respectively. This phenomenon could be due to the variability of the foot strikes the stairs either with the forefoot or with the heel [27] [28]. Based on the observation during the experiment, it could be observed that normal individuals tend to strike the stairs with the forefoot, whereas obese individuals tend to strike the stairs with the heel. This situation was believed associated with the effort to reduce the effective moment arms distance in order to reduce the net joint moment generated at the ankle, knee and hip joint successively.

At middle stance, an abduction moment in obese and normal individuals was revealed which corresponded to a low generated energy confirmed by a stabilization configuration with only 14% and 37% of the joint moment contributing to the joint power, respectively. The low generated energy produced at this time instant maybe associated with the weight acceptance activity of the hip joint which required a low energy to produce such movement [10].

At late stance-phase, a flexion-extension, an abduction-adduction, and an internal-external moments were comparably higher for obese than for normal individuals. For obese individuals, this situation corresponded to a high absorbed energy confirmed by a resistance configuration with 77.7% of the joint moment contributing to the joint power. In contrast, for normal individuals, this situation corresponded to a lower absorbed energy confirmed by a stabilization configuration with only 27.5% of the joint moment contributing to the joint power. The higher absorbed energy for obese than for normal individuals was maybe due to more important anterior mass transfer in order to push the body forwards and upwards to the next step for each ascending stairs [1]. This phenomenon was believed associated with a higher joint moment produced at the hip joint for obese than for normal individuals [4].

As a conclusion, the high variability of the joint dynamics of the stair ascending activity for the obese and normal individuals could be due to base on the two main factors: (1) The individuals' ability to control their centre of mass within a constantly changing base of support (2) The individuals' capacity to adapt strategies to accommodate changes in the stair environment [28].

V. CONCLUSION

The hip 3D joint mechanics seems to be a good approach to investigate and to highlight the difference of the hip joint gait strategies used between the obese and normal individuals during stair ascending activity. In general, both subjects tend to stabilize the joint, however, at the late stance phase of the stair ascending activity, the obese individuals tend to resist instead of to stabilize the hip joint. In addition, the neuromuscular adaptation as a compensatory mechanism relative to the BMI has been proven with only a small proportion of the high hip generated moment of the obese individuals was contributed to the joint power in comparison to the normal individuals at the early and middle stance of the stair ascending activity.

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