Measurement and Comparison of Humaonid H7 Walking with Human Being

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Abstract. This paper describes our research efforts aimed at understanding human being walking functions. Using motion capture system, force plates and distributed force sensors, both human being and humanoid H7 walk motion were captured. Experimental results are shown. Comparison in between human being with H7 walk in following points are discussed : 1) ZMP trajectories, 2) torso movement, 3) free leg trajectories, 4) joint angle usage, 5) joint torque usage. Furthermore, application to the humanoid robot is discussed.

1 Introduction

Recently, research on humanoid-type robots has become increasingly active, and a broad array of fundamental issues are under investigation (ex. [1–5]). In particular, techniques for bipedal dynamic walking, soft tactile sensors, motion planning, and 3D vision continue to progress. Humanoid robot is regarded as a general shape in human environment, its walk & balance function should be adapt to various terrain.

Current successful humanoids walk are mostly based on ZMP(Zero Moment Point) criteria [6]. Biped walk is achieved by satisfying ZMP over a time, since ZMP criteria itself is transient condition. In order to satisfy ZMP throughout biped motion, many predifined parameters are required. However, those parameters are hard to modify in terms of walking speed, energy consumption and stability. Actual humanoid walking is far unstable from that of human being has, therefore it can be efficient to investigate human walking.

In bio-mechatronics area, there are long history for measure and analyze human walking motion, and for example, inverted pendulum model of the walk is originaly proposed [7]. Motion capture system is commonly used to analyze human walking motion. Many researches has been proposed for analyzing and comparing handicapped/aged people walking motion with normal people walking(ex. [8]).

In this paper, we use motion capture system in order to measure and investigate both our humanoid H7 and human being walking.

2 Humanoid H7

Humanoid "H7" (H:1470mm, W: 55kg) (Fig.1 left) was originally designed at JSK(Inoue-Inaba Lab.), University of Tokyo and it was manufactured by Kawada Industries Inc. Concept of H7 is software research platform for humanoid robot autonomy, and in order to achieve this goal, mechanical components, sensing system, and computational availability are improved from previous H6 robot [9].

2.1 A Fast ZMP Tracking Trajectory Generation Method

Since a humanoid robot has many degrees of freedom, position-based trajectory generation has been adopted mostly using a ZMP criteria. Several remarkable methods have been proposed using ZMP criteria mostly applying to biped walking pattern generation [3, 10–12].

2.2 Dynamics Model of Humanoid Type Robot

First, we introduce a model of humanoid type robot by representing motion and rotation of the center of the gravity (COG). Let z axis be the vertical axis, and x and y axis be the sagittal and lateral plane respectively. Set m_i, $\boldsymbol{r}_i = (x_i, y_i, z_i)$, w_i, $\boldsymbol{I}_i$ be weight, position, angle velocity, inertia moment of ith link respectively. Let total mass of the robot be m_{all}, and total center of the gravity be $\boldsymbol{r} = (r_x, r_y, r_z)$. Then they are represented as follows:

$$m_{all} = \sum m_i, r_x = \frac{\sum m_i r_{x_i}}{m_{all}}, r_y = \frac{\sum m_i r_{y_i}}{m_{all}}, r_z = \frac{\sum m_i r_{z_i}}{m_{all}} \tag{1}$$

Let moment around its center of gravity be $\boldsymbol{M}_c$, total force that robot obtains from the floor be $\boldsymbol{f} = (f_x, f_y, f_z)$ and total moment around a point $\boldsymbol{p} = (p_x, p_y, p_z)$ be $\boldsymbol{T}$, then dynamic equation around a point $\boldsymbol{p}$ is represented as follows:

$$\begin{aligned} m_{all}(\boldsymbol{r} - \boldsymbol{p}) \times (\ddot{\boldsymbol{r}} + \boldsymbol{g}) + \boldsymbol{M} - \boldsymbol{T} = 0 \\ \boldsymbol{f} = m_{all}(\ddot{\boldsymbol{r}} + \boldsymbol{g}) \end{aligned} \tag{2}$$

ZMP position $\boldsymbol{p} = (p_x, p_y)$ around point $\boldsymbol{p} = (p_x, p_y, h)$ on the horizontal place $z = h$ is defined as a point where moment around point $\boldsymbol{p}$ be $\boldsymbol{T} = (0, 0, Tz)$, and it can be calculated from Equation 2.

$$p_x = r_x - \frac{M_y - m_{all}(r_z - h)(\ddot{r}_x + g)}{m_{all}(\ddot{r}_z + g)} \tag{3}$$
$$p_y = r_y - \frac{M_x - m_{all}(r_z - h)(\ddot{r}_y + g)}{m_{all}(\ddot{r}_z + g)}$$

Let $h = 0$ in Equation 3 and using Equation 2, then ZMP can be calculated as follows when desired robot motion has been achieved [13].

$$p_x = r_x - \frac{M_y - m_{all} r_z(\ddot{r}_x + g)}{f_z} \tag{4}$$
$$p_y = r_y - \frac{M_x - m_{all} r_z(\ddot{r}_y + g)}{f_z}$$

2.3 Stabilization by Horizontal Center of Gravity Position Modification

Let $\boldsymbol{p}^*(t)$ be the given ideal ZMP trajectory, and $\boldsymbol{Q}(t)$ be the whole body trajectory (ex. walking motion trajectory). When robot moves along given $\boldsymbol{Q}(t) = \boldsymbol{r^o}(t)$, then resulting moment $\boldsymbol{M}^o$, force $\boldsymbol{f}^o$, ZMP $\boldsymbol{p}^o$, center of gravity $\boldsymbol{r}^o$ is calculated.

Problem statement and compensation scheme are defined as follows:

Problem Statement: For given ideal ZMP trajectory $\boldsymbol{p}^*(t)$ and given input body trajectory $\boldsymbol{Q}(t) = \boldsymbol{r}^o(t)$, calculate an approximate new trajectory $\boldsymbol{r}^*(t)$ that causes a new ZMP trajectory $\boldsymbol{p}(t)$ which is close enough to the given ideal ZMP trajectory $\boldsymbol{p}^*(t)$.
From Equation 4, following equations is obtained for both in ideal and current $\boldsymbol{p}, \boldsymbol{r}$ respectively.

$$p_x(t) = r_x(t) - \frac{M_x^o(t) - m_{all} r_z(t)(\ddot{r}_x^o(t) + g)}{f_z^o(t)} \tag{5}$$
$$p_x^*(t) = r_x^*(t) - \frac{M_x^*(t) - m_{all} r_z^*(t)(\ddot{r}_x^*(t) + g)}{f_z^*(t)}$$

Compensation Scheme: In order to simplify Equation 4, only horizontal modification of the body trajectory is considered.

Since only horizontal compensation motion of the body is considered, $r_z^o = r_z^*$. Then, two assumptions are introduced:

Assumption 1 We assume that effect to the force $\boldsymbol{f}(t)$ that robot obtains from its self motion is small enough. Therefore,

$$\boldsymbol{f}_z^o(t) = \boldsymbol{f}_z^*(t) \tag{6}$$

Assumption 2 We assume that effect to the torque around center of gravity that robot obtains $\boldsymbol{M}(t)$ from its self motion is small enough. Therefore

$$\boldsymbol{M}^{o}(t) = \boldsymbol{M}^{*}(t) \tag{7}$$

With these assumptions, and let $\boldsymbol{p}^{err}(t)$ be an error between ideal ZMP $\boldsymbol{p}^{*}(t)$ and current ZMP $\boldsymbol{p}(t)$, and $\boldsymbol{r}^{err}(t)$ be the an error between ideal center of gravity trajectory $\boldsymbol{r}^{*}(t)$ and current trajectory $\boldsymbol{r}(t)$.

$$\begin{aligned} \boldsymbol{p}^{\boldsymbol{err}}(t) &= \boldsymbol{p}^{*}(t) - \boldsymbol{p}(t) \\ \boldsymbol{r}^{\boldsymbol{err}}(t) &= \boldsymbol{r}^{*}(t) - \boldsymbol{r}(t) \end{aligned} \tag{8}$$

Therefore following result is obtained from Equation 5 and Equation 8.

$$\boldsymbol{p}^{err}(t) = \boldsymbol{r}^{err}(t) - \frac{m_{all} r_z(t) \ddot{\boldsymbol{r}}^{err}(t)}{f_z^{o}(t)} \tag{9}$$

2.4 Solving Differential Equation

Equation 9 can be solved as subtract approximation. By discretizing Equation 9 with small time step $\triangle t$ with iteration $i, (i = 0, 1, 2, \ldots, n-1, n)$,

$$\begin{aligned} \boldsymbol{p}^{err}(t) &\rightarrow \boldsymbol{p}^{err}(i) \\ \boldsymbol{r}^{err}(t) &\rightarrow \boldsymbol{r}^{err}(i) \\ \ddot{\boldsymbol{r}}^{err}(t) &\rightarrow \frac{\boldsymbol{r}^{err}(i+1) - 2\boldsymbol{r}^{err}(i) + \boldsymbol{r}^{err}(i-1)}{\triangle t^2} \end{aligned} \tag{10}$$

Then trinomial expression which satisfies $r^{err}(i)$ is obtained when $1 \leq i \leq n-1$.

$$a_i r^{err}(i-1) + b_i r^{err}(i) + c_i r^{err}(i+1) = d_i \tag{11}$$

Here,

$$\begin{aligned} a_i &= -\frac{m_{all} r_z^{o}(i)}{f_z^{o}(i) \triangle t^2} \\ b_i &= 1 + 2\frac{m_{all} r_z^{o}(i)}{f_z^{o}(i) \triangle t^2} \\ c_i &= -\frac{m_{all} r_z^{o}(i)}{f_z^{o}(i) \triangle t^2} \\ d_i &= p^{err}(i) \end{aligned} \tag{12}$$

Table 1. Comparison of Major Body Parameters

link	Human Being	Humanoid H7
Height [cm]	168.3	147.0
Weigth [kg]	61.4	53.5
Foot w[kg]	1.1	1.8
Foot l[cm]	7.3	6.0
Shank w[kg]	3.1	3.3
Shank l[cm]	39.0	30.0
Thigh w[kg]	6.6	2.9
Thigh l[cm]	35.7	30.0

Then using boundary condition of trinomial expression, boundary condition $i = 0, i = n$ is calculated. In this paper, we fix terminal position. If statically stable posture is given as the terminal posture, both end of resulted trajectory will not be moving.

– Since terminal position is fixed, x_0, x_n are given.
– From position and acceleration of center of gravity relationship, number of variables is $n - 1$ from $t = 1$ to $t = n - 1$.
– From ZMP constraint, number of variables is $n + 1$ from $t = 0$ to $t = n$.

As for boundary condition, terminal velocity is indefinite, we set the following boundary conditions.

$$\begin{aligned} b_0 &= b_n = 1 \\ a_0 &= a_n = 0 \\ c_0 &= c_n = 0 \end{aligned} \tag{13}$$

Given coefficient matrix, trinomial expression is solved, and discrete $\boldsymbol{r}^{err}$ is calculated. We have shown the method is fast enough for online walking pattern generation [14].

Given parameters for generate walking trajectory Q are, ideal ZMP trajectory p^*, foot placement position and timing, free leg trajectory, upper body trajectory (torso horizontal position will be modified by this method). Then proposed algorithm can generate modified torso trajectory r^* that satisfies ZMP trajectory p^*. Since there are so many parameters, we would like to investigate biped walk of human being.

3 Walk Measurement and Analysis

Fig.1 shows humanoid robot H7 and human being walk in motion capture system. Table 1 shows dimensions of each subject. Motion capture system that has seven cameras is produced by Vicon, and two force plates are utilized. Analysis is done by using right side of one cycle step (from landing to end of air phase).

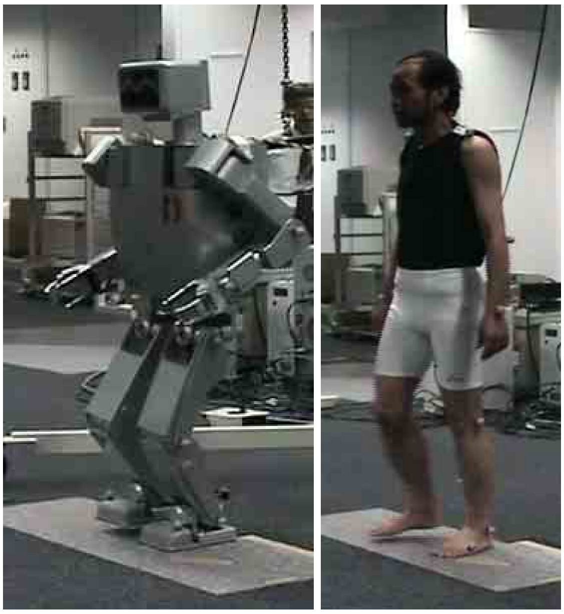

Fig. 1. Motion capture scene for humanoid H7 and human being while they are walking

In order to capture human being motion, marker of the motion capture system is attached to torso(3), hip(4), knee(2), ankle(2), and foot(6). Therefore, total 17 markers are attached both for human and humanoid H7.

Hip joint position is calculated 18% interpolated to the line that connects two outside hip markers. Both knee and ankle joint positions are assumed to be modeled by only one DOF. Those joints are parallel with each other, and it is perpendicular to the triangle of knee, ankle and foot heel markers. Knee joint is 2.6% inside that is perpendicular to the knee marker, and ankle joint is 2% respectively. Marker resolution is about 1[mm].

Link weight for human being is calculated by approximating each link by cylindroid. Link weight for a robot is taken from 3D mechanical CAD data (CATIA). From floor reaction force and body parameters, inverse dynamics calculation is utilized to calculate joint moment, joint torque and joint power.

Using those link parameters and force plates, inverse dynamics calculation was applied to calculate joint torque and power.

4 Comparison

Since the body dynamics and actuator mechanisms of H7 and human being are not the same, only qualitative analysis can be achieved. Especially energy consumption mechanisms will be quite different. There are several remarkable difference in between H7 and human walk motion.

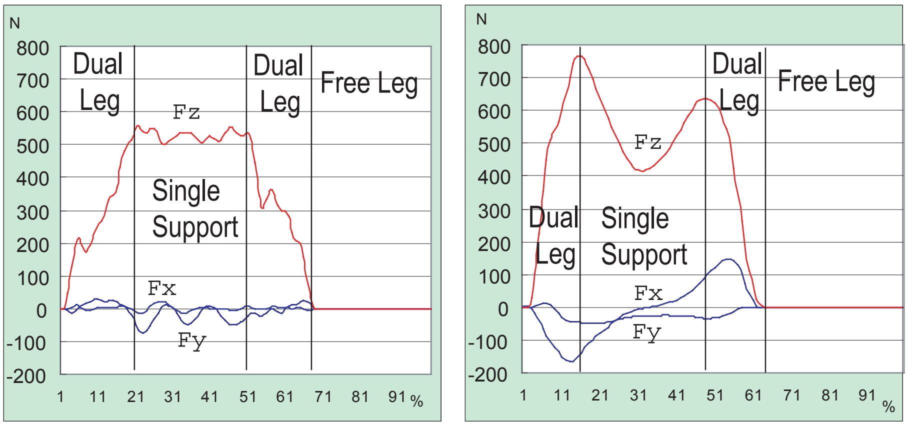

Fig. 2. Three Axis Floor Reaction Force for 1 Cycle of Right Leg: H7 (left), Human (right)

4.1 Floor Reaction Force

Three floor reaction forces of one cycle of right leg are shown in Fig.2. Left side of Fig.2 shows forces of H7, and right side shows that of human being. F_z of H7 shows almost its weight during single support phase, and during dual leg phase F_z gradually shifts from/to the other leg. However F_z of human dual leg phase shows 20-30% heavier weight, and 20-30% lighter in middle of single leg support phase.

As for F_x, F_y of H7 are almost flat because given ideal ZMP position is not moving inside the foot. However human uses F_x, F_y which can be regarded that human uses frictions on the floor.

4.2 ZMP Movement

Fig.3 shows the result of foot force distribution sensor and ZMP trajectory. According to our walking trajectory generation method mentioned in section 2., ZMP trajectory is given of the algorithm. In this paper, we gave the center point of the foot(Fig.3 left). However, human uses heel for landing and ZMP position is quickly move to around the ball of the thumb(Fig.3 right).

4.3 COG Movement

Fig.4 (upper) shows vertical movement of center of gravity (COG). H7 keeps its COG height at constant height as designed. Human being COG height shifts according to leg phase. It has two cycle in one walking cycle. The lowest height is in middle of dual leg phase, and the highest is middle of free leg phase.

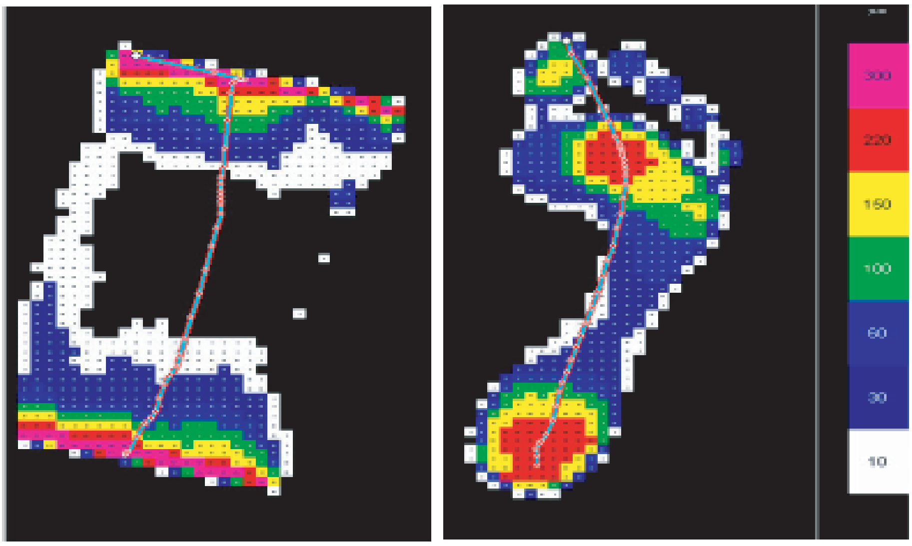

Fig. 3. Distributed Floor Reaction force for 1 Cycle of Right Leg (0-300 [kPa]) : H7 (left), Human (right)

Also, Fig.4 (lower) shows horizontal movement of COG and ZMP. H7 shifts its COG about 16cm in order to satisfy given ZMP trajectory. However, human COG movement is about 3cm, even shifting ZMP trajectory in horizontal direction.

H7 doesn't move its COG in vertical direction. This is also given parameters from our walk trajectory generation method. Human COG trajectory moves in vertical direction. Vertical movement of COG doesn't have any meaning for energy consumption.

Also floor reaction force F_z maximized at the dual leg phase, human can use higher friction of the ground with small disturbance around yaw-axis. Instead in single leg phase, human has equivalently small weight that causes small horizontal movement of the COG.

4.4 Knee Joint Angle

Fig.5 (middle) shows knee joint angle. H7 uses knee joint for lifting up its foot at free leg phase. Human bends its knee at both dual leg phase and extend at single support leg phase (double knee action). However joint angle in single support phase doesn't reach straight nor rock (hyperextension). Instead, the end of free leg phase, human knee joint reach about strait or rock position.

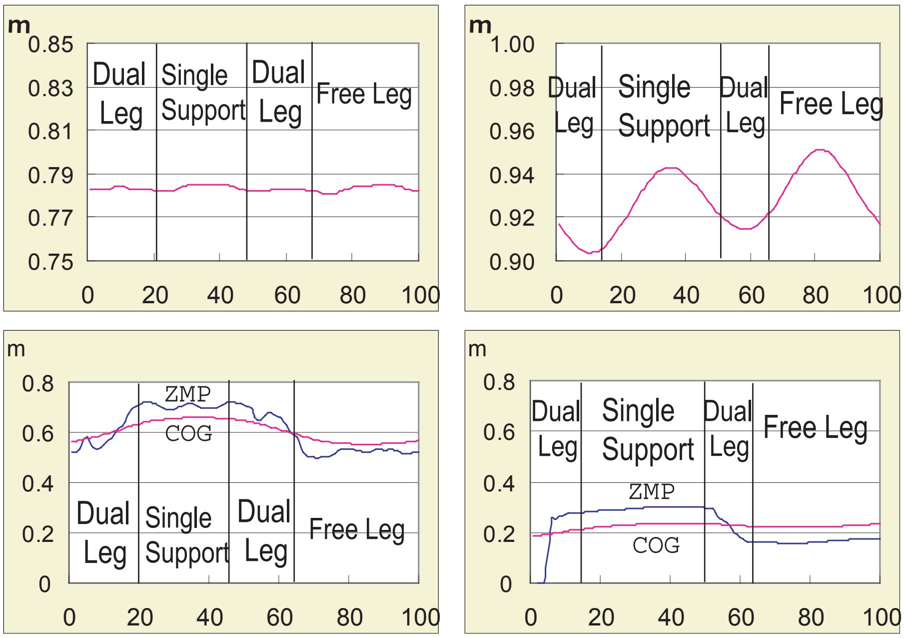

Fig. 4. Sagittal Movement of Center of Gravity (upper) and Latteral Movement of CoG/ZMP (lower): H7 (left), Human (right)

4.5 Hip Joint Moment

Fig.6 (upper) shows hip joint moment. H7 doesn't use hip joint moment since walking speed is quite small. However, human has quite remarkable two peak in both dual leg phase. Considering the other leg phase is 180[deg] different with this graph, resulted total hip joint moment will balance around yaw(Z)-axis. This symmetric usage of hip joint moment is known in bio-mechanical field.

4.6 Free Leg Trajectory

H7 lifts its free foot by using knee joint (Fig.5 middle left). Foot was kept parallel to the ground by using ankle joint in order to avoid collision. However, human foot angle is not always parallel to the ground. During the dual leg phase, human launch its body by using both leg (as mentioned in Section 4.5), and the accelerated body lifts the free leg. Torso roll angle was just only 2[deg] for help lifting free leg.

4.7 ZMP Trajectory Design

H7 tries to put its ZMP at center of the foot so that robot can have maximum stability for any direction. However, human being has very asymmetric ZMP trajectory for both lateral and sagittal direction.

5 Conclusion

In this paper, walking motion comparison of our humanoid robot H7 and human being is described. Since many parameters are different (including link parameters, walking speed, step length, step cycle and mechanisms), discussion about energy consumption, balance control scheme are not achieved. However, we found several interesting difference by qualitative analysis, especially 1) Free leg trajectory, 2) COG movement, and 3) ZMP trajectory design. We would like to improve humanoid walking trajectory generation method and balance compensation method by using those information.

Also those measurement system is very important for developing a humanoid walking system, since only dead-reckoning results are obtained by using onbody sensors. So we would like to use this environment for evaluate internal sensors and for develop humanoid walking function for uneven terrain.

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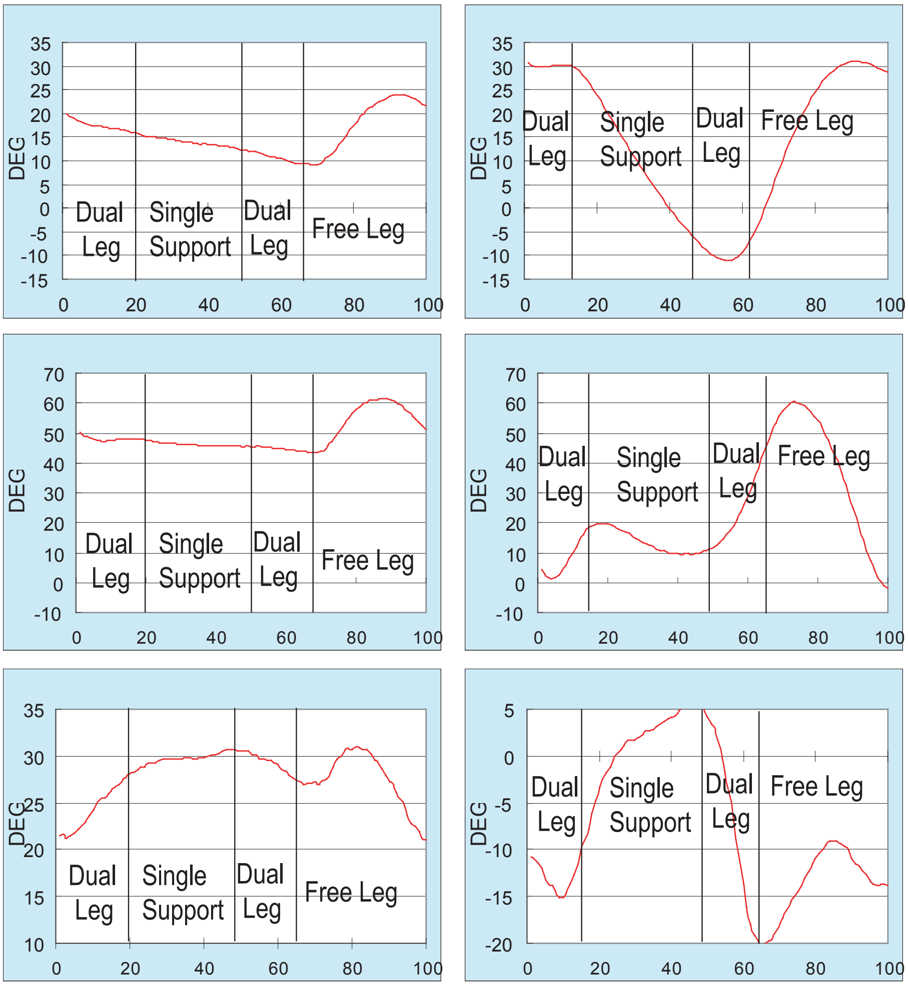

Fig. 5. Hip(top), Knee(middle), Ankle(bottom) Pitch Joint Angle: H7 (left), Human (right)

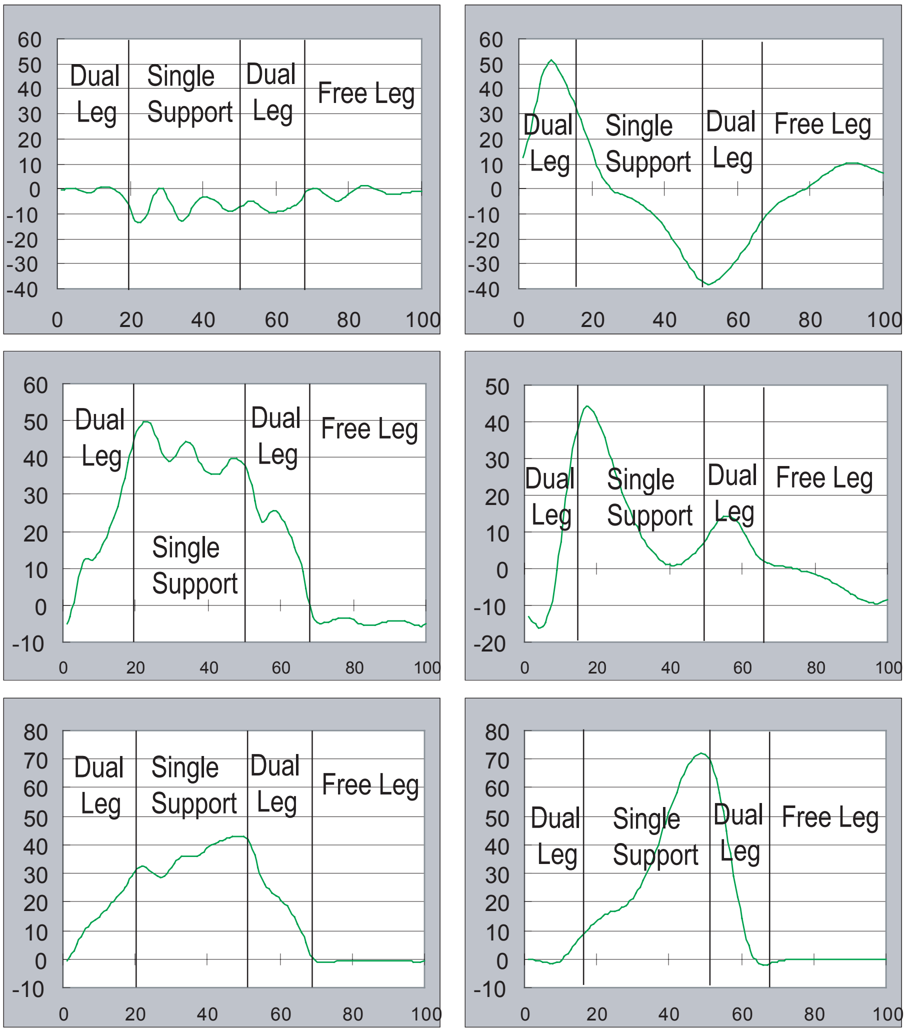

Fig. 6. Hip (top), Knee(middle), Ankle(bottom) Pitch Joint Moment: H7 (left), Human (right)