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An auto-adaptable algorithm to generate human-like locomotion for different humanoid robots based on Motion Capture Data

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Abstract— **The work presented in this paper deals with the generation of trajectories for humanoid robots imitating human gaits captured with a motion capture system. Once the human motion is recorded, this one is modified to be adapted to the robot morphology. The proposed method could be used for human-like robots of different sizes and masses. The generated gaits are closed to the human's ones while respecting the robot balance and the floor contacts. First the human joint angles are computed from the markers coordinates and applied directly to the robot kinematics model. Then, from this non-corrected motion, the trajectories of both feet and of the Zero Moment Point (ZMP) are generated respecting the constraints of floor contact and balance control. From this data, an inverse kinematic algorithm is used to compute the joint angles of the robot according to the feet and ZMP trajectories. The results with the robot HRP-2 (AIST, Kawada Industries, Inc) and the small-sized humanoid HOAP-3 (Fujitsu Automation Ltd) are compared with the human motion.**

I. INTRODUCTION

The idea to generate humanoid motions from human motion capture is mainly within three scientific fields: biomechanics, computer graphics and robotics. On this topic, biomechanics deal with the analysis of pathological subject gait in order to characterize the walking pathologies and finally finding an individual functional rehabilitation method or a surgical solution. Our motion capture method is based on the experience of biomechanics community [1] especially for the choice of marker sets and segment (a limb considered as a rigid body) axis definitions. Computer graphics [2] focus on the use of motion capture and synthesis movement to generate three-dimensional realistic movements for virtual models including non anthropomorphic models as well. This is related to the present work since the problem is how to transform the motion of a human with a special size to a humanoid robot with different dimensions, masses and inertias. The gap between these diverse fields is beginning to be closed through the work of multi-disciplinary teams. For instance a dance recorded by motion capture was learned and reproduced by the Humanoid HRP-2 [3]. More recently HRP-4C imitates a human female walking and turning [4]. The Honda research institute proposed an online transfer of human motion [5] but only for the upper part of the robot ASIMO.

The main contribution of this work is to adapt the computer graphic techniques for retargetting motion to new characters [2], [6] to generate trajectories for humanoid robots of different sizes imitating a human motion. The relevance of the proposed method is demonstrated with the results on a small sized robot (HOAP-3) and on a human-like sized robot (HRP-2) which is quite unusual in the literature. Compared to the computer graphic applications, the difficulties for the humanoid robots is to respect the feet/floor contacts and the dynamic balance. To imitate the human locomotion captured, this paper presents a new approach based on the control of feet motion and CoM (Center of Mass) trajectories. The maximum speed of the computed gait is found in order to respect the ZMP (Zero Moment Point) criterion [7].

The motion capture process and the analysis of the human locomotion is presented in the next part. Then the principle of the motion adaptation is detailed with its key points: the feet motion definition, the balance constraint, and the specific solver. The last part of this paper presents the results of the motion adaptation to the human-sized robot HRP-2 and to the small-sized robot HOAP-3.

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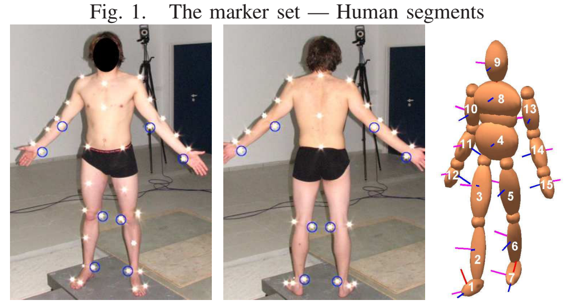
II. HUMAN LOCOMOTION

A. Motion capture

Thirty seven reflective markers (Fig. 1) are placed on the subject skin (Fig. 1). To collect kinematic data i.e. to record the trajectories of the markers, a motion capture system is used with six cameras located around the studied area.

Fig. 1. The marker set — Human segments



Ankle, knee, elbow and wrist joint centers are considered as located in the middle of their internal and external markers. This method is currently used by the biomechanics community [8], [9]. The shoulder and hip joint centers are not easy to locate precisely. Two main methods are available for their location. The first one called predictive method uses several characteristic limb dimensions of the subject to locate the joints according to the markers [10]. However joint angles and inverse dynamic results are sensitive to the location of joint centers, this method is not as accurate as the second one called functional method. This one is based on a computation of joint center locations from a kinematic analysis of imposed movements corresponding of ten cycles of flexion, abduction and circumduction [11]. In the present approach the functional method is used in order to determine the joint centers and thus the joint trajectories. The number of segments chosen is fifteen (Fig. 1) which is sufficient to transpose the motion to a humanoid robot (feet, shins, thighs, pelvis, thorax, arm, forearm, hands, head). Most of humanoid robots are designed with this kinematic architecture [12]. The wrist and neck joint are not considered in this study. The hands and the head follow respectively forearms and the thorax. The segment axis are chosen according to the International Society of Biomechanics' recommendations (ISB) [1] except for the feet in order to simplify the definition of angles. In the reference anatomic position, human model segment y-axis are pointing upwards, while x-axis are constructed to be close to the walking direction.

B. Human joint angles computation

To extract any segment movement in the reference coordinate system (called R_0), at least three markers are needed to build the segment coordinate system. The rotation matrix $Rot(S_i/R_0)$ of each segment Si is computed with respect to R_0. Then the rotation of the segment i with respect to the coordinate system of the segment $i-1$, the matrix $Rot(S_i/S_{i-1})$ is computed. Finally the yaw-pitch-roll sequence is used to identify the intersegmental angles called abduction, flexion and rotation.

C. Foot contact events

The next step of the process is to compute the human foot contact events. Indeed, to generate a feasible gait for the robot, the single (one foot on the floor) and double support (both feet on the floor) phases must be defined. The foot contact events: Initial Contacts (IC) and Toes take Off (TO), are identified only with the kinematic data. A recent gait event detection algorithm called the high pass algorithm (HPA) [13] is extended for the present application. Kinematics of markers on the lateral malleolus and metatarsal are used (Fig. 2). It was necessary to modify this algorithm because it was developed for human gait in a straight line while more complex locomotion are transposed to the robot. The modification is to use not only the marker displacements along one axis (walking lane axis in the original case) but the curvilinear abscissa in the horizontal plane. For a non cyclic gait with a quarter turn at the end, the two first IC and TO are compared to the measurement of two force plates located on the walking lane. The contact on each foot is detected when the vertical force is higher than 5N [14]. The error on events is less than 40ms. We consider that this error is acceptable for the transposition process.

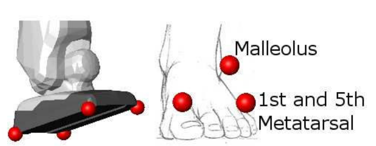


Fig. 2. Feet markers for HRP2 and for the human subject

D. CoP and CoM trajectories

To verify the gait event detection, two force platforms were used. The collected data contain also the trajectory of the center of pressure (CoP) during gait. The force platforms provide the results from the beginning of the first single support phase to the end of the second one (Fig. 3). During the double support phase, the CoP is computed from both platforms.

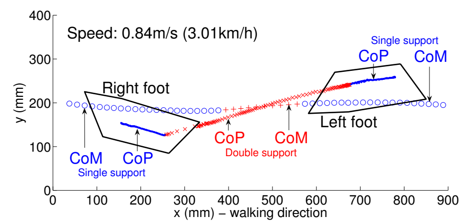


Fig. 3. Measured forces of the platforms (500Hz) — Subject center of pressure and center of mass projection on the floor

During the single support phase, the CoP moves from the back to the front along the main axis of the foot. The CoP is slightly on the external part of the foot. After the single support, the CoP changes immediately its direction, because only the toes of the first foot are in contact with the ground. The CoP moves from external to internal toes. At the same time, the heel of the second foot enters in contact with the force platform. During the double support phase, the CoP moves in "straight line" from the end of single support position to the beginning of second single support.

The CoM trajectory is computed from anthropometric data [15]. The CoM projection on the ground follows a sinusoidal curve as it is described in many papers [16]. The amplitude of these oscillations are small compared to the CoP transverse displacement. This gait is clearly dynamic and non quasi-static. At the beginning and the end of the single support phase, the CoM lies outside the sustentation polygon which means that the static balance is not respected.

III. MOTION ADAPTATION

A. The idea

To imitate the captured human motion with a humanoid robot, a first approach could be to control the robot as a marionette [17], imposing the human joint angles to the humanoid. This approach will not create a feasible motion since the robot has not necessary the same geometry and mass repartition. The motion adaptation transforms the human locomotion to a feasible motion for a chosen robot. Two main constraints must be respected by the adapted motion. First, any part of feet cannot interfere with the floor and they cannot slide on the ground during single and double support. Secondly the robot dynamic balance must be respected at any time.

The algorithm i started(Fig. 4) by a computation of the non adapted robot motion. The joint angles extracted from human motion captured are directly imposed to the robot joints. The translation according to the earth reference frame

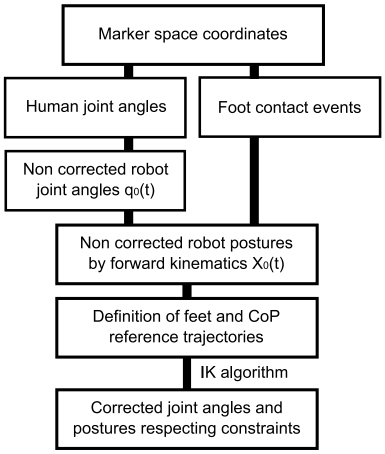


Fig. 4. Process overview

is defined by the back internal point of the right or left foot. During a walking step, this point of the foot on the floor is assumed fixed to the ground. Moreover the orientation of the robot with respect to the earth reference frame is defined by the orientation of its hips which is equal to the orientation of human hips. This method permits to generate feet trajectories really close to the human ones while taking into account the segment lengths of the robot. If the robot is smaller than the human subject, the walking step size changes, the walking speed is automatically smaller, but the gait frequency is the same.

B. Feet motion definition

The different phases of the feet/floor contacts (Fig. 5) are described below:

- t1: The left heel touches the floor
- t1-t2: The front foot turns around its heel
- t2-t3: Both feet stay flat
- t3-t4: The back foot turns around its toes
- t4: Toes take off, start of the single support
- t5: Maximum altitude of the heel
- t6: Maximum altitude of the toes
- t7: Heel landing

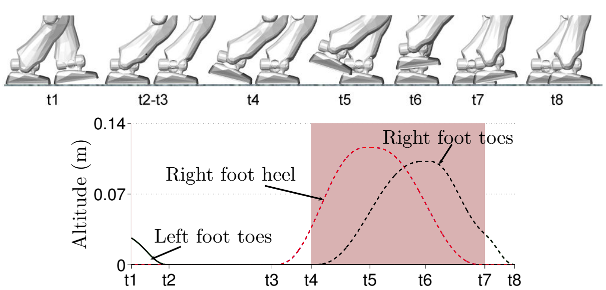


Fig. 5. Example of feet trajectories and altitude of heels and toes during a walking step

The Fig. 5 presents an example of imposed altitudes of heels and toes. Between the different time ti, the trajectories are defined with sixth order polynoms in order to insure continuity of position, velocity and acceleration. The desired position of the different points are coming from the non-corrected motion $X_0(t)$ (Fig.4) for the positions depending on the robot dimensions, or directly from the motion capture. For instance, the translation of the feet in the walking direction is found from the non-corrected motion computed from the human joint angles. For each initial contact, the position of the front foot for $X_0(t)$ will be the target of the reference feet trajectory. The orientation of the robot's feet will correspond to the orientation (only yaw and pitch) of the human's ones for each initial contact. The parameters necessary to generate the desired feet motion could be summarized in the following (Fig. 5):

- At t1: Altitude of forward toes, position of one point for each foot, feet orientations
- At t5: Maximum altitude of swinging heel
- At t6: Maximum altitude of swinging toes
- At t7: Altitude of swinging toes, position of one point for the swinging foot, swinging foot orientation

The obtained trajectories can be compared to the human's ones (Fig. 6-7). For the human subject, only three markers for each feet are known: the lateral malleolus, the 1st and 5th metatarsus (Fig. 2). For the robot, the position of the four extremities of the sole are presented.

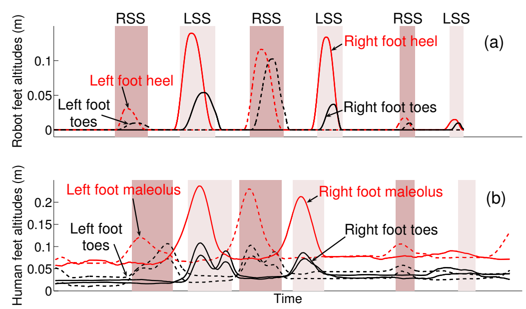


Fig. 6. Altitudes of toes and heels of the robot (a) and the human subject (b)

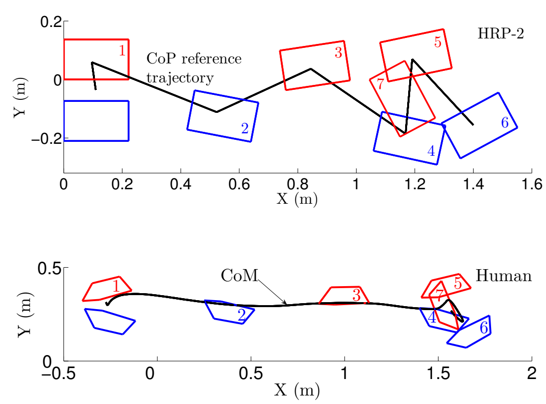


Fig. 7. Reference trajectories of feet and CoP of the robot and measured trajectories of the feet and CoM of the human subject

Concerning the vertical position (Fig. 6), we observe that the heel trajectories are well reproduced by the robot while the toes trajectories are more difficult to imitate with this method. The trajectories of the feet on the floor are quite well reproduced (Fig. 7). The initial position is different since the robot starts with its feet parallels while human feet are not parallels in the initial posture. A final step (Fig. 8) is added to generate a stable and symmetric posture at the end of the motion (Fig. 9).

C. Balance

The Zero Moment Point [7] (ZMP) trajectory is controlled to ensure the robot balance. The ZMP is always in the polygon defined by the edges of one or both feet on the ground. During single supports, the ZMP should progress along the foot direction with sufficient security margins. As shown in Fig. 7, for HRP-2 as well as for HOAP-3, a null displacement is imposed to the ZMP during this phase since the balance is really better in this way. During the double supports the ZMP moves in a straight line from the back foot to the front foot. As for the feet reference trajectories, the ZMP trajectory is defined with 6^{th} order polynomial to ensure continuity of position, velocity and acceleration.

Most of walking pattern generation algorithms do not control directly the ZMP trajectory. It is not a simple geometric task since it depends on derivative of joint angles. On the other hand, the CoM is considered as a geometric task, it can be control by inverse kinematics (IK). The preview control of an inverted pendulum model [18] can be used in order to find a trajectory of the CoM which will lead the ZMP to follow the reference. Thus, using an IK algorithm, the joint angles could be computed to perform the walking pattern.

The ZMP will not follow exactly the ZMP reference trajectory since the inverted pendulum model is a broad approximation of a humanoid. Thus a second pass of the preview control is needed to reduce the modeling error between the pendulum and the multibody model. A drawback of this method concerning the imitation of human locomotion is that the CoM has to stay at the same altitude during gait or has to follow a special curve. Nevertheless this method has demonstrated its relevance and its robustness on many experiments on different platforms [18].

The computation of the CoM trajectory is not the main subject of this paper. This one describes a generic approach of the proposed method. That is why the study is limited to a quasistatic balance approach, which one, as the pendulum method, consists in controlling the CoM location. For example, a dynamic walking reproducing a human slalom was also generated for HRP-2 [19].

With the IK algorithm the CoM projection is constrained to follow the reference trajectory, then we find the maximum speed in order to respect the ZMP criterion. The ZMP did not follow exactly the reference (Fig. 8) since the dynamic effect can not be neglected but it stays in the sustentation polygon. In the presented example, the walking step lengths are artificially decreased compared to the human's ones (Fig. 8) in order to obtain feasible step lengths for a quasistatic walk. Indeed as it is demonstrated in Fig. 7, the captured human walk is a dynamic gait, the gait frequency is high and the average length of walking step is high. If the subject walks with a quasistatic balance, the step lengths and the gait frequency are lower. That is why the step lengths are chosen lower in this case.

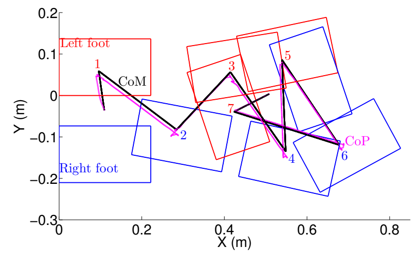


Fig. 8. Positions of the single supports during motion with decreased lengths of the walking steps for a quasistatic walking generation for HRP-2

D. Solver

The damped least squares method [20] (IK algorithm) also called Levenberg-Marquardt method (1) is chosen for its speed and robustness to respect the constraints of balance and feet motion at each time step. To respect the joint limit constraints, a second term (2) is added to the IK equation. Δq_i and Δx_i are respectively the small displacements of the joints and of the task. J is the standard jacobian, J^+ its damped pseudo inverse, α a scalar parameter, I the identity matrix. $\nabla\phi$ is the gradient of the joint limit constraint function [21] computed from the current joint coordinates qt and the joint limits.

$$\Delta q_i = J^+ \Delta x_i + \alpha (I - J^T J) \nabla \phi \tag{1}$$

$$\nabla \phi = \frac{(q_{max} - q_{min})^2 (q_{max} + q_{min} - 2q)}{(q_{max} - q)^2 (q_{min} - qt)^2} \tag{2}$$

We start from the previous computed posture $X(q_{t-1})$ to the new one $X(q_t)$, except at the first time step. As described in section III-A, the robot position and orientation according to the earth reference are defined respectively with the position of one foot and the orientation of the pelvis. The task comes from the constraints described before, the eleven components could be detailed as follow:

- 3: Orientation of the non-moving foot
- 3+3: Orientation and position of the swinging foot
- 2: Axial and transverse position of the CoM

$X(q_t)$ are the eleven coordinates of the points concerning by the constraints computed with the joint coordinates q_t. The goal is to find the vector q_t such as $X(q_t)$ are respecting the conditions. Only the twelve DOF q_t of the locomotor system are modified by inverse kinematics, upper limbs DOF follow the subject motion according to the robot joint limits and without auto-collision. As the forward kinematic model, the jacobian matrix is computed in a literal way but the damped pseudo inverse is found from a numerical computation at each time step. The iterative procedure is stopped when X_t^i is sufficiently close to its goal X_{Gt}. A precision of $\varepsilon = 5.10^{-5}m$ is chosen. This value seems to be acceptable according to the result of the simulation on the OPENHRP software. A greater value of ε would decrease the computational time but it would induce instabilities during initial contacts and toe off. In this paper a constant precision of the feet and CoP position is chosen. However, the precision could be changed for the different phases, indeed during single support, we could accept a larger error of the swinging foot position. During the start (toe off) and the end (initial contact) of the single support, its movement has to be defined precisely since impacts could appear.

IV. APPLICATIONS AND RESULTS

A. HRP2 and HOAP-3

The Figure 7 reports the human motion adapted for the humanoid HRP-2 and for the small-sized robot HOAP-3. The locomotor systems of both robots are composed by twelve DC motors, six for the hips, one for each knee and two for each ankle. Concerning the upper part, only ten actuators are used in our example. The joints of wrists (only for HRP-2), hands and the neck stay in the initial position. Twenty two angles are generated by the algorithm. The main dimensions, masses and inertias of the robot are different from the human's ones. An overview of the adapted motion is presented in Figure 9. Figure 8 represents the position of the robot's feet during its displacement. The walking speed is lower than the human's one. Indeed, the legs of HRP-2 and HOAP-3 are smaller than the human's ones but in addition the human dynamic gait is transformed to a quasistatic one. The motion of the upper limbs are not significant since the human subject during his motion did not move significantly his arms. The robot starts with ankle-knee-hips angles equal to 20-40-20° for HRP-2 and 5-10-5° for HOAP-3. All the others joints start with a null position. The last posture is the same as the initial one. The robot balance is validated for HRP-2 with the virtual environment software OPENHRP. The robot walking trajectories are originals because during the double support phase the robots use the front and back edge of their feet. Moreover the trajectories reproduce not only the position of the feet on the floor but also the orientation of the feet at several times during walking.

V. DISCUSSION

The proposed method is more focused on the imitation of human locomotion compared to the project of the leg task models for enabling a biped humanoid robot to imitate human dances [3]. In this context, more parameters are defined in the leg task model especially during the double support phase. The front foot turns around its heel edge then both feet are flat and the back foot turns around its toes. These parameters taken into account lead to obtain a humanoid robot trajectory closer to the human one's. Even the sustentation area decrease at these times, the robot stays upright. These new results on HRP-2 and on HOAP-3 enable us to generate an anthropomorphic walking pattern for those robots and permit to increase the step length as it is shown in [22]. Thanks to the retargetting methods [2] in the computer graphic community, the feet and CoP trajectories are automatically adapted to the controlled humanoid robot (length, architecture and mass repartition).

VI. CONCLUSION

An auto-adaptable algorithm to generate human-like locomotion for humanoid robots is described in this paper. This one is based on Motion Capture Data and allows to robots with different sizes to imitate the captured human motion. The motion capture process is detailed since a new approach was developed to determine the foot contact events i.e. the double and single human support phases. Moreover the results from the force platforms show that the CoP trajectory during walking is closed to the common reference ZMP trajectories for humanoid robot. The motion adaptation process is developed to be efficient for robots with different sizes and structures. The feet motion and ZMP reference trajectories are defined by 6th order polynomials. The feet motions include during the double support phases a heel strike and a delayed toe off. This choice was made to be closer to the human feet motion. Usually in humanoid robotics both feet stay flat during the double support phase. Concerning the robot balance, a classical ZMP reference trajectory is proposed and validated on the software OPENHRP. The robot joint angles respecting the feet motion definition and the ZMP trajectory are computed using a specific IK algorithm based on the Levenberg-Marquardt method including the joint limit constraints. The joint trajectories computed in our case are smooth and acceptable for the robots. The obtained results show the efficiency of the method and it will enable to quickly generate humanoid walking trajectories imitating human locomotion.

VII. ACKNOWLEDGMENTS

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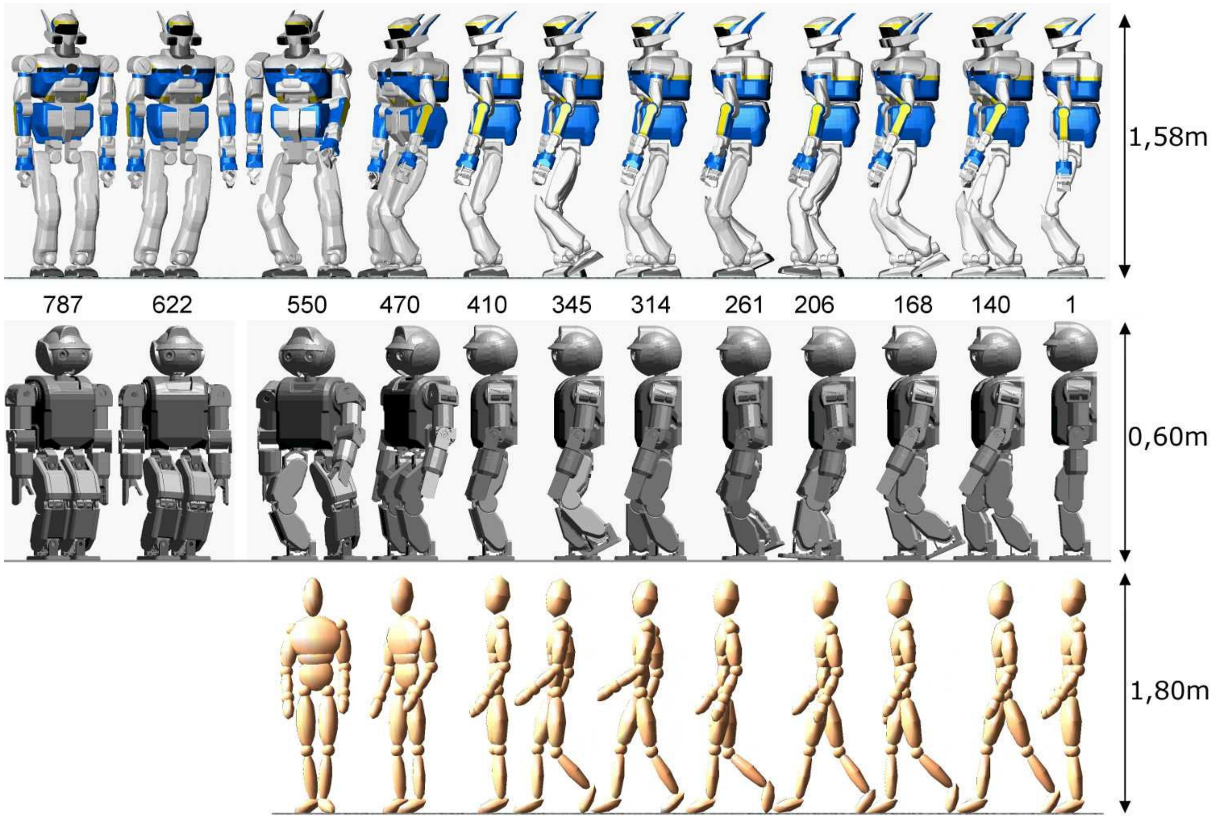

Fig. 9. Motion obtained after computation for HRP-2 and HOAP-3 compared to the human motion

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