STUDY OF POSTURAL ADJUSTMENTS FOR HUMANOIDAL HELPMATES

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Abstract:

Humanoid robots and humans look alike, and therefore are expected to adjust their posture in a similar way.

We analysed a set of human static postures that should be considered for humanoids acting as caretakers. A dynamic situation was studied to learn how humanoids can react in a dynamical way. Human data were obtained with a professional motion capture system and anthropometric tables.

The static postures were studied using a segmented human body model, but for motion analysis the single and double pendulums with moving masses were also employed. For robot motion synthesis we need to know the relation between the posture and the postural stability.

We have shown that the positions of mass centres of the pendulum segments (which match the human body point masses) are crucial for postural stabilization. The Zero-Moment Point criterion was applied for the dynamic case. The static analysis demonstrates that there are some common features of the postures. The dynamic analysis indicated that both pendulums are good models of human body motion, and are useful for humanoid motion synthesis.

In humanoids, it is easier to apply results represented by inverted pendulums than postural models represented by stick diagrams. This is because humanoids and humans do not obviously share the same mass distribution and sizes (proportions) of all body segments. Moreover our descriptions indicate where to locate the supporting leg/legs in single and double support, which in general, is missing in inverted pendulum models discussed in the literature.

The paper's aim is to deepen the knowledge about the adjustment of human postures for the purpose of robotics.

Keywords: centre of mass, zero moment point, anthropometric data, postural stabilization

1. Introduction

Postural stability is crucial for humanoid motion synthesis. Humanoids should move in similar way to human beings. The actual research objective is to deliver methods for autonomous and human-like postural adjustment.

Having humanoids that can perform more actions like a person means they can be used as human helpmates or caretakers. Stabilization of humanoids has been studied in many works, some examples are [10, 13, 24]. This problem is treated from different perspectives, some works use neurobiological inspiration [4,14], other researchers are applying the pure theoretical approach [7, 11, 19, 22, 23], or the human postural data are considered [3, 18]. It can be noticed that inverted pendulum models are often used as simplified descriptions of human body dynamics [1, 7, 8, 12, 15, 19] allowing the investigation of postural stability measures.

Nowadays it is more common to get inspiration from nature, one of such examples can be found in [17] where the model of human sensing was used for postural control synthesis that allowed the robot's motion response to external stimuli to be comparable to those of the human being.

Our objective was to investigate the postural adjustment during different activities, this was achieved by observing and recording a set of human postures and analysing the obtained data.

To obtain information on how stable postures are achieved, our analysis included two situations: i) static cases for describing typical static postures that can be used (repeatedly) by assistive robots, ii) a dynamic case for investigating how the motion of body parts helps recover the lost stability. For investigating the postural stability, different models of the human body were used.

In [17] the single inverted pendulum was applied in order to study the upright stance, while a model with 8 links and point masses was used in [9] to analyse the stability of humanoids during walking with both, rigid and compliant feet.

In [16] it was demonstrated that the kinematics and ground reaction forces for single and double inverted pendulums are similar. In [20] the inverted pendulum models were used to represent the gait stance phase, an enhanced model was also proposed.

To evaluate the dynamic stability, the Zero-Moment Point (ZMP) criterion is used. In [21] it was demonstrated that during double support the centre of pressure (CoP) and the ZMP are equivalent if both feet are on the same planar surface.

Different methods have been used to observe and record the human body adjustments, in [2] photographic techniques and motion capture systems were applied. As mentioned in [5] the new methods include the use of 3D cameras, force platforms, and more affordable devices like the Microsoft Kinect^m and the Nintendo Wii Balance Board^m. The recording technology that is used depends on the aim of study and the required accuracy of the results.

2. Postural Stability

The ZMP criterion was originally defined for single support phase and is used to investigate the postural stability during motion. The definition that we present in this section is based on [25].

The ZMP is the point where the resultant reaction force vector must be applied in order to produce the moment equilibrating the moments due to body motion dynamics. In other words, the ZMP is the point that makes Eq. 1 true.

$$M_x = 0$$

$$M_y = 0$$
(1)

If the computed ZMP is located outside the footprint area of the supporting leg, the resultant reaction force vector is actually applied at the foot edge, which causes the body to rotate and leads to its falling.

The ZMP criterion is used to verify if the body is in dynamic equilibrium. There are two support phases that need to be considered - single and double. For each of them, the support polygon is different: i) during single support (when only one foot is on the ground) it is the ground area covered by the supporting foot, ii) for double support (when both feet are in contact with the ground) it is composed of the contact area of both feet and the ground area between them.

3. Human Body Models

For robot motion synthesis it is crucial to know the correlation between the posture and the postural stability [12].

The anthropometric data used for the postural stability analysis include: i) the mass of each body segment (expressed in the literature as a percentage of the total mass of a person), ii) the length of each body segment (expressed as a percentage of the height of a person), iii) the location of each centre of mass (CoM, expressed as the ratio of each segment length with respect to the proximal end of the segment).

The segmented model was used for both, the static and dynamic analyses. It divides the body into 11 segments and takes into account the anthropometric data. The model is shown in Fig. 1.

The segmented model was used to evaluate the location of the masses in more compact models, which were the inverted pendulums.

Tab. 1 shows the anthropometric data as percentage of the length and mass of each body segment, those values were used to specify the segmented model.

The information about the position of the CoMs was considered when evaluating the postural stability for the set of still postures. For this study we obtained the position of the overall CoM or of the CoMs of the upper and lower sections of the body. The position of a CoM that combines two or more partial masses is expressed by Eq. 2, where k is the overall amount of partial masses that are being combined and m_i is one of



Fig. 1. Segmented model of the human body. The stars mark the location of each CoM

them. The equation shows how to obtain the x coordinate, but for 3D cases similar formulas are applied for the remaining coordinates.

$$x_{CoM} = \frac{\sum_{i=1}^{k} m_i \cdot x_i}{\sum_{i=1}^{k} m_i}$$
(2)

The single and double inverted pendulum models with moving masses were used for the dynamic analysis.

The length of the single inverted pendulum was equal to the height of the person minus the distance between the ankle and the ground (0.048 of total body height for women and 0.043 for men [6]). The position of the pivot point of the pendulum depends on the gait phase, during single support it is the same as for the ankle of the supporting leg, while for double support it is located between both ankles. In Fig. 2, we can see the single pendulum obtained from the segmented model shown in Fig. 1.

The double inverted pendulum has the same total length and pivot point as the single one. To build this pendulum, it was decided to divide the body at the waist. This means that with respect to the height of a person, the lower segment length is equal to 0.584 for women and to 0.587 for men, while for the upper segment length it is equal to 0.368 for women and to 0.370for men. Fig. 3 shows the double pendulum model at

Tab. 1. Used anthropometric data

Segment	Segment Weight/ Total Body Weight	Centre of Mass/ Segment Length	Segment Length/Height Woman Man	
Forearm and hand	0.022	0.682	0.152	0.145
Upper arm	0.028	0.436	0.193	0.189
Foot and shank	0.061	0.606	0.234	0.242
Thigh	0.100	0.433	0.242	0.245
Abdomen and pelvis	0.281	0.270	0.108	0.100
Thorax	0.216	0.820	0.193	0.189
Head and neck	0.081	1.000	0.0714^{*}	0.0743^{*}

The data in the columns "Segment Weight/Total Body Weight" (segment weight divided by the total body weight) and "Centre of Mass/Segment Length" (location of mass centre position measured from the segment proximal end, and normalized to the segment length) were obtained from [26]. The data shown in both columns of "Segment Length/Height" (segment length normalized to the body height) were obtained from [6], with the exception of the normalized values marked with *, which were obtained directly by us. Note: the anthropometric data taken from the literature were consistent with those of the tested persons.





the same time instant shown of Fig. 1.

The location of the CoMs of both pendulums are obtained by using the data of the segmented model.

4. Static Analyses

To analyse the static analysis we focused on 6 typical postures. For each of them, a person was asked to pose in the same way they would when getting ready



Fig. 3. Double pendulum model used during the dynamic analysis. The stars mark the location of the upper and lower CoMs

to perform an action, and to keep both soles in contact with the floor. In every case, a picture was taken in order to draw a segmented model. The postural adjustment is personal, moreover for the same person it can differ from case to case, in our work we were not aiming to repeat many trials for producing the data as the personal average is characteristic. For our studies we only needed a reliable example of the human behaviour, therefore the participant was a healthy woman without motion disorders and with normal body build. The aim was to investigate the position of the overall CoM (and its projection to the floor) depending on the postures. This advises how the total CoM location should be adjusted in a humanoid robot.

To compensate the visual distortion in the picture, we measured the tested person and scaled the length of each body segment with respect to the upper arm. This means that the pictures were only used to evaluate the relative position of the body segments.

The pictures were taken from such point that nominally minimalised the inaccuracy in the position evaluation. Since they were taken with a normal automatic photo camera, the grid lines were used in order to try to adjust the position with respect to the floor. The person was asked to hold a posture and not to exert any force on the objects that were part of the scenario. The body segments and their ends were marked, as shown in Fig. 4.



Fig. 4. Markers used for the static analysis

To decide which postures to study, we considered some scenarios that can be useful for humanoids that take care of people. These are:

- Starting posture for pushing an object: here, there are two options, in Fig. 5 we can see the posture when a person is prepared to push a light object, while in Fig. 6 we can observe how it is when the object is heavy. In both cases, the two hands are used.
- Starting posture for pulling an object: as before, we have two options, in Fig. 7 we can see the posture when a person is prepared to pull an object by using both hands, and in Fig. 8 we can observe how it is when only one hand is used.
- Starting posture for collecting an object from a



Fig. 5. Segmented model for a person prepared to push a light object. The black dots mark the location of each segment CoM



Fig. 6. Segmented model for a person prepared to push a heavy object. The black dots mark the location of each segment CoM

height: Fig. 9 shows the posture of a person which is trying to take an object from the top of a storage with both hands.

- Starting posture for passing an object: Fig. 10 shows the posture of a person taking an object when it is close to her, and Fig. 11 shows the posture used



Fig. 7. Segmented model for a person prepared to pull an object by using both hands. The black dots mark the location of each segment CoM



Fig. 8. Segmented model for a person prepared to pull an object by using one hand. The black dots mark the location of each segment CoM

when the object is farther. Here the action is considered to be done by using only one hand.

- Starting posture for collecting an object from the floor: in Fig. 12 we can see the posture of a person taking an object from the floor with both hands. In this case adjusting the length of the "thorax" and the "ab-



Fig. 9. Segmented model for a person prepared to collect an object from a height. The black dots mark the location of each segment CoM



Fig. 10. Segmented model of a person prepared to take an object that is close. The black dots mark the location of each segment CoM

domen and pelvis" was needed because the position of the markers did not allow to depict the sizes properly. To obtain these values, the length of each segment was directly measured as a straight line connecting their ends while the back was bent.

- Starting posture for opening a cupboard's doors: Fig. 13 shows the posture of a person before opening doors that are at a certain height.



Fig. 11. Segmented model for a person prepared to take an object that is far. The black dots mark the location of each segment CoM



Fig. 12. Segmented model of a person prepared to collect an object from the floor. The black dots mark the location of each segment CoM

For those postures we evaluated the location of the overall CoM projection onto the floor and obtained the reaction forces on both feet. We made two assumptions: i) when both feet are on the same x position, the overall ground reaction force is divided equally between them, in this case it is possible to obtain the location of the application point for the leg-end force vectors; ii) when the feet are in different x positions, the application points of the reaction force vectors are at the ankles (such simplification allows to compute the value of the reaction forces).

All the results shown in Tab. 2 were computed by using Matlab.

When the ankles are together, the application points of the reaction forces (and the overall CoM projection) are located within the soles. In the cases

Fig. 13. Segmented model for a person prepared to open the doors of a cupboard. The black dots mark the location of each segment CoM

where the ankles are at different positions, the projection of the overall CoM is located between both feet, this means that it stays within the support polygon which allows the posture to be stable.

The postures in Fig. 9 and Fig. 13 are similar, this shows that a small number of postures can be used to represent many actions. This is an important observation, because it is not possible to study all the postures a person can perform.

In Tab. 2, for 5 out of 9 postures the smaller force is at the front of the overall CoM (for pushing, this is F_L and for the other ones it is F_R). In most of these postures both arms are in the front of the body (Fig. 5, Fig. 7, Fig. 9 and Fig. 13).

Only for the two postures in which the ankles are apart (Fig. 6 and Fig. 10), the reaction force acting on the frontal foot is greater. But for a general conclusion, more situations need to be studied.

5. Dynamic Analysis

One recorded data set was analysed, however several recordings were done for general confirmation of the general repeatability of reaction (the human responses to the push are not identical but hold similar features). The recordings were done by using a motion capture system and the "Plug-in Gait" protocol to place the markers on the person. The communication protocol is served automatically by the VICON system and the user does not have access to it. A VICON system with assisting software was used.

The person was a healthy woman without motion

Tab. 2. Data obtained from static analysis

Starting posture for	x_{CoM} (cm)	F_{LR} (N)	F_{RR} (N)	F_L (N)	F_R (N)
Pushing a light object (Fig. 5)	29.3840	220.7250	220.7250	175.2557	266.1944
Pushing a heavy object (Fig. 6)	29.1433	108.2870	333.1630	246.3291	195.1209
Pulling with both hands (Fig. 7)	12.5190	220.7250	220.7250	361.5476	79.9025
Pulling with one hand (Fig. 8)	11.9603	220.7250	220.7250	173.9313	267.5187
Collecting object from a height (Fig. 9)	19.6618	220.7250	220.7250	273.2576	168.1925
Taking a close object (Fig. 10)	17.9394	336.3817	105.0683	241.4732	199.9769
Taking an object that is far (Fig. 11)	11.5548	220.7250	220.7250	164.2194	277.2306
Collecting object from the floor (Fig. 12)	16.5266	220.7250	220.7250	307.6907	133.7594
Opening a cupboard's doors (Fig. 13)	13.5135	220.7250	220.7250	273.2576	168.1925

The location of the overall CoM projection on the *x*-axis (x_{CoM}) is shown in the figure of each segmented model. When the feet are apart, the CoM projection is marked with an "x", and when they are together it is at the same position as the reaction forces acting on the left and right foot - F_{LR} and F_{RR} , respectively. F_L and F_R represent the forces due to the gravity acting on the left and right of x_{CoM} , respectively.

disorders and with normal body build. The action consists on four main parts: i) a person moves one step forward into a force plate; ii) when both feet are on the force plate, the person is suddenly pushed to the left; iii) in order to find a stable posture, the person moves her arms and legs; iv) finally, the person goes back to the force plate and then to her initial position.

The push situation is not a case which can be repeated with identical result, which is also difficult for typical gait since the leg-end trajectories are not identical for every step. Our aim was not to conclude about the statistically relevant pattern of this response but to analyse the motion dynamics using the inverted pendulum approach.

To read the recordings, the 3D Motion Kinematic & Kinetic Analyzer (Mokka) software was used. These data were combined with anthropometric data because the markers did not always indicate both ends of each segment. Both pendulum models were obtained by using Eq. 2 for the x coordinate and similar formulas for the remaining ones.

To compute the ZMP Eq. 3 was used, here F represents the total reaction force, the subscript s is for the support (ankle joint or pivot point of the pendulum), and N represents the amount of partial masses that compose the model for which the ZMP is computed.

$$P_{x} = \frac{\sum_{i=1}^{N} F_{z}(x_{i} - x_{s}) - \sum_{i=1}^{N} F_{x}(z_{i} - z_{s})}{\sum_{i=1}^{N} F_{z}} + x_{s}$$
$$P_{y} = \frac{\sum_{i=1}^{N} F_{z}(y_{i} - y_{s}) - \sum_{i=1}^{N} F_{y}(z_{i} - z_{s})}{\sum_{i=1}^{N} F_{z}} + y_{s}$$
(3)

To compute the reaction forces it was necessary to obtain the acceleration of each body segment at every time instant. For this, Eq. 4 was used to compute the velocities (using the actual and future CoM coordinates p), then these results were used in Eq. 5 to obtain the accelerations. Both, the velocities and accelerations were computed for each axis.

$$v_{i+1} = \frac{p_{i+1} - p_i}{\Delta t} \tag{4}$$

$$a_{i+1} = \frac{v_{i+1} - v_i}{\Delta t} \tag{5}$$

Finally, knowing the values for the acceleration and the mass of each segment, it was possible to compute the reaction forces using Eq. 6, where the gravity constant is $g = 9.81 \frac{m}{s^2}$.

$$F_x = \sum_{i=1}^{N} m_i a_{xi}$$

$$F_y = \sum_{i=1}^{N} m_i a_{yi}$$

$$F_z = \sum_{i=1}^{N} m_i (a_{zi} + g)$$
(6)

To investigate how the motion of the double pendulum masses is related, we used Eq. 7, here *n* represents the amount of samples used - total of the recorded instants of time. By removing the summation from the numerator of the correlation equation we obtained a motion correlation measure for each instant of time.

$$r_i = \frac{(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$
(7)

5.1. Obtained Results

Fig. 14 shows the first method we used to obtain the ZMP trajectories using the segmented model, for double support the projection of CoP was used as an approximation of the ZMP trajectory. The dashed lines connect the ZMP trajectories that were computed for single and double support phases.

To obtain the location of the CoP, we defined the overall force in the z direction to be linearly divided between both feet depending on the location of the overall CoM. In this case, again, the reaction forces were assumed to be located at the ankles. This is shown in Eq. 8 where the *ratio* was used to obtain the value of the vertical component of the reaction force on the right foot (F_{RRz}), here d_{L_CoM} is the distance along the xy plane from the left ankle to the overall

CoM and d_{LR} is the distance along the xy plane between both ankles. Finally, with both results, we evaluated the vertical component of the reaction force on the left foot (F_{LRz}).

$$ratio = \frac{d_{L_CoM}}{d_{LR}}$$

$$F_{RRz} = ratio \cdot F_z$$

$$F_{LRz} = F_z - F_{RRz}$$
(8)

Using Eq. 9 with the previously obtained data and the reaction forces coordinates, it is possible to compute the location of the CoP.

$$CoP_{x} = \frac{x_{RR} \cdot F_{RRz} + x_{LR} \cdot F_{LRz}}{F_{z}}$$

$$CoP_{y} = \frac{y_{RR} \cdot F_{RRz} + y_{LR} \cdot F_{LRz}}{F_{z}}$$
(9)

In both plots (Fig. 14 and Fig. 15), the support phases are represented by three colours: i) green for double support, ii) blue for right single support, iii) and red for left single support. The footprints are shown, and the black line represents the trajectory of the projection of the overall CoM. The arrows indicate the ZMP and the CoM displacement.

The second method is shown in Fig. 15 where the ZMP position in double support phase is approximated by connecting the ends of the trajectories obtained for consecutive single support phases. It can be noticed that in the second case there is a good coincidence between the ZMP and CoM projection, and that the first method of ZMP approximation in double support gives a significant discrepancy between the ZMP and the CoM projection. This indicates that the second method of ZMP approximation is more accurate.

Fig. 14. ZMP results for the segmented model - using the CoP to obtain it for double support

In Fig. 16 the ZMP trajectories for both pendulums are shown, in red for the single one and in blue for the double one. One can notice that the trajectories obtained with both pendulums are similar to those in Fig. 15, and also that they are similar to each other. This brings the conclusion that both pendulums are good representations of the human body, this observation

Fig. 15. ZMP results for the segmented model - using lines connecting the values for single support phases to approximate the ones for double support

is consistent with [16] which stated that both models have similar features.

Fig. 16. ZMP trajectories for single and double pendulums

Fig. 17 (the different colours distinguish each support phase) shows the normalization of the distance from the beginning of each segment (pivot point or waist) to its CoM (d_{rod_CoM}) with respect to its segment length (l_{rod}). For this, Eq. 10 is used and both values are in mm. We can observe that the motion trend of both CoMs is similar, especially at the interval between 6 and 10s, which is approximately the time when the person is pushed and goes back to the force plate.

$$normalization = \frac{d_{rod_CoM}}{l_{rod}}$$
(10)

Fig. 18 (the colours indicate the support phases) presents the correlation measure obtained by using the results from Fig. 17 in Eq. 7. Here, positive values mean that both CoMs move simultaneously upward or downward, and the greater the value is, the displacement is more similar. It is possible to see that in overall, the correlation is positive. We divided this plot into some stages: i) hands up (when the person's arms are

Fig. 17. Position of the double pendulum CoMs normalized to the length of each rod. The first plot is for the lower segment and the second plot for the upper one

Fig. 18. Correlation measure at each instant of time between the upper and lower mass position (normalised data were considered as they are shown in Fig. 17). For better explanation, small sketches of the human posture are displayed

stretched to the sides more than during normal walking), ii) hands down (when the person's arms are close to her body, similar to their position during normal walking), iii) balancing (after the person was pushed and before she is able to start going back to the original position), iv) correcting step (from the time when the person started moving back to her original position until the first foot was placed again on the force plate). During the "balancing" and "correcting step" phases, the correlation measure increases, but it starts decreasing when normal standing is approached again. These values are coherent with the behaviours shown in Fig. 17. We can also observe that the correlation tends to be greater during sudden motions (see Fig. 18 at the interval between 6 and 8s), this happens in single support phases. During double support phases, the lowest correlation measure is present when the person is in standing position with small or no visible motion, the measure is almost constant but in the final double support, we can notice that the correlation measure increases due to the fact that the person's body sways backward.

6. Conclusions

Knowledge of the CoM position is relevant for transferring the postural adjustment patterns to humanoids.

The dynamic case confirmed that similar results can be obtained with the single and double pendulums. However the latter one has an advantage, because it helps to understand how the motion of the upper and lower body influences the position of the resultant CoMs. Such model can help to adjust the postural stability in humanoids by deciding when and how to move the arms or legs in order to make each CoM reach a specific location.

The analyses of the static cases indicated that the total reaction force vector should be applied at the same location as the projection of the overall CoM in order to maintain the postural equilibrium. We also observed that the projection of the overall CoM is always within the support polygon. The results also explain how the posture of a humanoid can be adjusted depending on what it is expected to do. The postural stability is assured when the location of the projection of the overall CoM is within the support polygon, this can be achieved by adjusting the posture and measuring if the ratio of the feet reaction forces is similar to the one obtained for human beings.

By computing the ZMP it was possible to see that in this case the CoP was not a good approximation for double support due to the fact that the location of the force acting on each feet was assumed. But, when that happens, it was proven that using straight lines to connect the ZMP values for single support phases is also a good approximation.

Here we could also demonstrate how different technologies can be used to study the human body motion, in this work we used photographic techniques and a motion capture system. With both inverted pendulums, we could also verify that the results obtained by using them are similar, which proves both are good representations of the human body.

As future work, we suggest: i) to use the spring loaded inverted pendulum model for non-typical cases and to see if other considerations are necessary in order to use it for different motion situations, ii) to study the energy that people require to perform non-typical actions (i.e. to find a stable posture after being pushed). Combining all the information can help answer in what manner we can define the human motion synergies for the purpose of robotics.

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