

# A Human-like Walking for the COmpliant huMANoid COMAN based on CoM Trajectory Reconstruction from Kinematic Motion Primitives

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**Abstract**—Research on humanoid locomotion made significant improvements over the last years. In most cases, though, the gait of state-of-the-art robots is still far from being human-like due to two main reasons. These are, the mechanical incompatibilities between the human and the engineered humanoid platforms, and the lack of clear understanding of the highly complex human walking motion itself. This work attempts to address the latter by using a novel method to construct locomotion trajectories for a humanoid robot based on *kinematic Motion Primitives (kMPs)* derived from humans locomotion trajectories. The work demonstrates how from a small set of invariant primitives it is possible to reconstruct all the joint trajectories to obtain different gaits, with different speed, and while accomplishing different tasks at the same time. We then used the proposed method to reconstruct a human-like CoM trajectory, and evaluate it on our COmpliant huMANoid robot, COMAN. Experimental results are presented to demonstrate the execution of a stable, fast walking, with knee straightening at toe-off to push forward, that strongly resembles a more human-like walking. Furthermore, and taking inspiration from the inherent passive compliance in the joints of the COMAN robot, the energy consumption of the robot was investigated by varying the frequency of the gait generated basing on the human kinematic primitives. The idea was to exploit the natural dynamics of the compliant humanoid platform, and minimize its energy consuption. Experimental results for different stepping frequencies in terms of energy consumption over a fixed time, and to walk for a fixed distance are presented.

## I. INTRODUCTION

Research on humanoid locomotion in the past years has led to significant improvement in the performance of robot walking in terms of stability and efficiency. However, most of the state-of-the-art robots still can't perform a human-like gait. The engineered motion trajectories based on different methodologies ([1] [2] [3] [4] [5] [6] [7] [8] [9]) are still very different from those found in human, and look not natural. If on the one hand intrinsic mechanical constraints has a strong effect on this result, on the other hand it is also evident that it is still not completely understood how humans synthesize such complex motions.

The first objective of the work presented in this paper is then to perform an analysis/study of human walking motion from the point of view of kinematics, in order to investigate it more in depth, and understand how to reproduce it on COMAN, a passive COmpliant huMANoid platform developed in IIT, to make its motion more human-like. The idea was to reduce the complexity of human motion, acquired with motion capture, by finding some features (kinematic Motion Primitives) that remain invariant. A similar analysis, but based on EMG signals, was presented in [10] and [11], where five invariant synergies were identified to describe with 90 - 95% of accuracy human locomotion, and three for the animal locomotion, respectively, when performing different tasks. Their work was based on the well known central pattern generation (CPG) theory. Though many are the works on CPG and motor primitives extraction from EMG signals, it is not easy to find in the literature a similar research based on kinematics. The work in [12] presented a research on the topic. In this work they propose a novel method to extract motion primitives from the ten joint trajectories with widest range of motion. The work demonstrates how these primitives, with a proper time-shifting, can be finally combined to produce different emotional walking trajectories. In the work done in [13], instead, dancers' motion was analyzed starting from the x,y,z trajectories of 32 markers.

Our work is closely related to these, and particularly aims at finding motion primitives from human walking at different velocities, also while performing simple manipulation tasks like holding an object. We call the primitives we extracted *kinematic Motion Primitives (kMPs)*. Starting from these motion primitives, then, we reconstructed a human center of mass (CoM) trajectory, and used it to perform a human-like walking with our humanoid robot, COMAN. Given the walking we obtained was highly dynamic, we also evaluate the behavior of our compliant humanoid by checking its performance to different stepping frequencies in terms of energy efficiency. The idea was to optimize the energy

consumption of the robot by tuning the frequency of the generated gait. The motivation for this study was due to the existence of the inherent passive compliance in the joints of the COMAN robot, which allows the exploitation of the natural dynamics, and therefore this can be used to minimize the energy consumption of the humanoid robot.

The paper is structured as follows. Section II presents the procedure and analysis used for the extraction of the kinematic Motion Primitives. Section III discusses the trajectory generation based on the reconstruction of the CoM from the motion primitives, and introduces some details of the compliant humanoid platform. Finally, Section IV comments on the effect of the modulation of the stepping frequency on the energy efficiency, and Section V concludes the work and discuss on further developments.

## II. EXTRACTION OF KINEMATIC MOTION PRIMITIVES (KMPs) FROM HUMAN GAITS

In order to collect data on human locomotion, five healthy, young (25 - 28), male subjects were asked to perform a set of motions on an electric treadmill. In total 39 passive markers were placed to fit a full body model, and a Vicon motion capture system with 6 cameras at 250 Hz, and the Plug-in Gait were used to monitor the trackers' position and reconstruct the kinematics (i.e., 34 joint trajectories). In Figure 1 you can see the experimental setup.

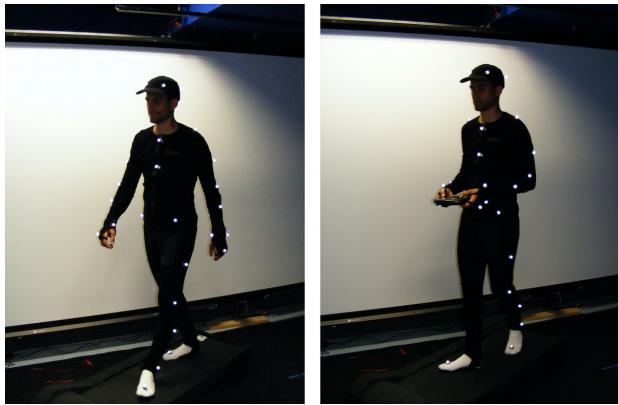


Fig. 1. Experimental setup with one subject performing a trial of normal walking, and a trial of walking holding a 5 kg load

The recorded trajectories were subsequently zero-mean normalized, and a Principal Component Analysis (PCA), an eigenvector-based multivariate analysis, was performed to reduce the dimensionality of data and extract possible motion primitives.

### A. Data Acquisition and Analysis

The five subjects were asked to perform five trials for each combination of the following velocities and tasks.

- Velocities
  - WLS - Walking at Low-Speed - 2 km/h
  - WHS - Walking at High-Speed - 4 km/h
  - RUN - Running - 6 km/h
- Tasks
  - Normal
  - B - Holding an empty box with two hands
  - 5 - Holding a 5 kg load with two hands

In this notation, for instance, WHS5 means walking high-speed holding a 5 kg load with two hands.

The overall number of trial per person was then 45, five for each of the nine different combinations analyzed. Only the trial with a low noise content were selected for Principal Component Analysis. In all cases, when considering only the first component, resulted in a reconstruction accuracy for the joint trajectories of an order of 50%. If both the first and the second components were considered, this percentage increased to approximately 80%. Adding the third component the reconstruction accuracy increased further to almost the 95%, while with the addition of the fourth primitive component the accuracy became 97.5%. The fifth primitive component brought the reconstruction accuracy to 99% of reconstruction accuracy in all joints trajectories. Figure 2 shows the results for various components from one trial. From these results five components were finally considered, since the addition of further components results in a very small improvement on the reconstruction accuracy of the joint trajectories.

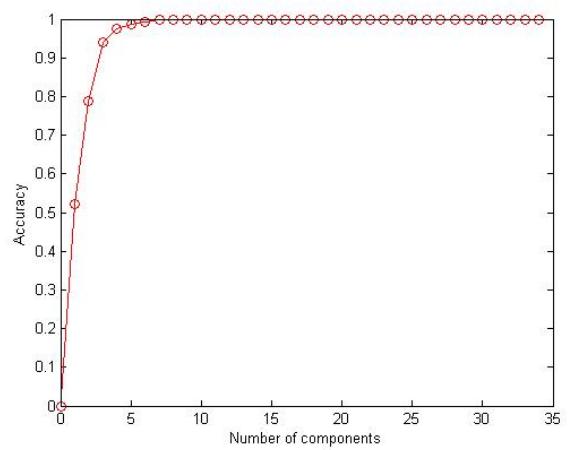


Fig. 2. Cumulative percentage of variance accounted for by principal components

Having extracted the kinematic Motion Primitives from the joint trajectories for each of the performed task, we compared the primitives to identify possible similarities or differences. Initially, normal (arm swing) walking at different velocities was considered focusing on the components of the different subjects in WLS and in WHS. These were normalized in time (from 0 to 100% of gait cycle) and amplitude (in each

component graph the maximum absolute value between all the subjects is 1; the ratio between different subjects is retained throughout, giving a better graphical visualization). Figure 3 shows the five components before and after normalization in amplitude, providing an indication of the ratio between components.

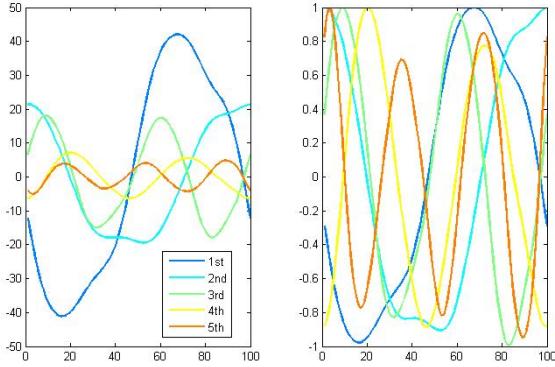
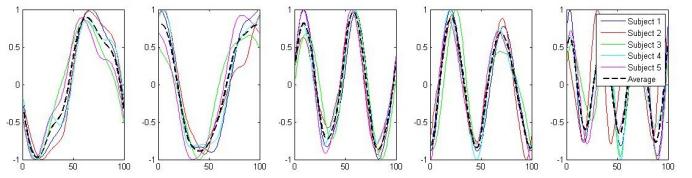


Fig. 3. The five components extracted by one subject, before and after normalization in amplitude

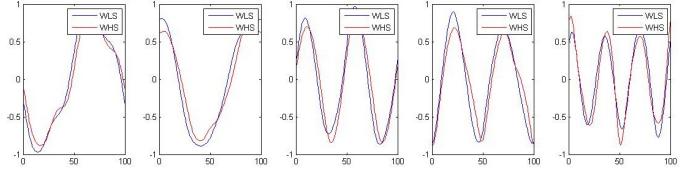
Having obtained the average components between the subjects, we compared them for the different velocities (WLS and WHS). Similarly, the RUN average components were derived and compared. Following this, we kept velocity fixed (WHS) and varied the task (normal, B - holding a box, 5 - holding a 5 kg load).

*1) Comparison of kMPs Among Different Subjects:* For the two normal walkings with different velocities (WLS and WHS) we compared the first five components from all five subjects. Figure 4(a) represents these components for the WLS motion. It can be observed that the shape is very similar for all subjects, as are the phase and the amplitude. The results for WHS were almost identical, confirming a good matching among the subjects. From these data it can be seen that the first and the second components have a frequency that is the same as the frequency of the gait cycle (two steps). The third and the fourth components have a frequency that is twice the frequency of the gait cycle. The fifth component has frequency that is three times the frequency of the gait cycle. As the first two components describe about the 80% of the joint trajectories, this indicates that most of the human motion is coupled with the frequency of the gait cycle. The third and the fourth components together describe about 17.5% of the trajectories. This motion is coupled with the single step. The remaining 2% (from the fifth component on) comes from motion at higher frequencies.

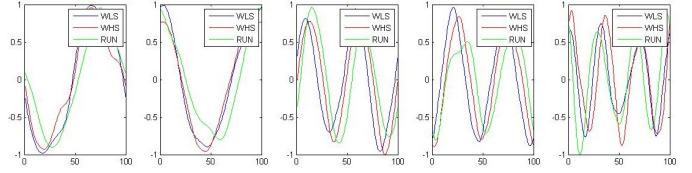
*2) Comparison of kMPs Among Different Velocities:* Once we demonstrated that different subjects walking in the same conditions (velocity and task) have a motion that is derived by the same primitives, we continued to compare these primitives



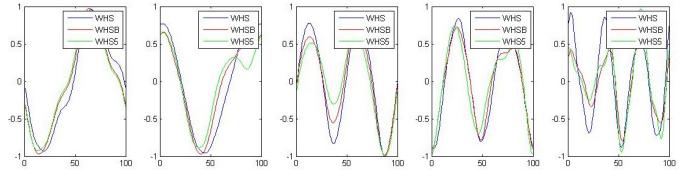
(a) Comparison between the components extracted from five subjects



(b) Comparison between: WLS and WHS



(c) Comparison between: WLS, WHS, and RUN



(d) Comparison between: WHS, WHSB, and WHS5

Fig. 4. The kinematic Motion Primitives

to those obtained when the walking conditions (velocity) change. First we compared the average five components of WLS with the average five components of WHS. As you can see in Figure 4(b) the components obtained for the two walking cases are very similar, demonstrating the effect of velocity change from 2 km/h to 4 km/h is very small. We then examined whether also the components extracted from the running gait were the same. In Figure 4(c) the components for all three cases (walking at different speeds and running) are shown. Since the tracking of the running gait was more noisy than the one of walking, we considered only the two subjects with the cleanest data. Looking at the shape of the primitives it can be noticed that also in the case of the running there is a great similarity. In certain cases there is a difference in terms of phase and amplitude, but it is almost negligible. Notice also that the difference between WLS and WHS is slightly bigger when data are from only two subjects. This is because the average between only two subjects is still affected too much by the peculiarity of the gait of the single subject. Hence, it is reasonable to assume that, if it was possible to use the data from all five subjects, also the difference between running and walking with two different speeds would have been reduced further.

3) *Comparison of kMPs Among Different Tasks:* Having observed that walking at different velocities and running can be generated by the same kinematic Motion Primitives, we further investigate if these primitives remain the same even if we introduce simple perturbation tasks to be accomplished while walking or running. For this reason we compared the primitives extracted from WHS to those extracted from WHSB and WHS5 (results are showed in Figure 4(d)). Also in this case only data from the two subjects with the cleanest trajectories were used. The reason why we selected to investigate the walking while holding an object was to introduce a constraint on the arms motion, which during normal walking is usually coupled with the motion of the legs. In the case of the box only a kinematic constraint was introduced, since the cardboard box weight was negligible. In the case of the 5 kg weight, instead, there was also a constant vertical force to counteract. Looking at the data obtained it can be noticed that even in these task scenarios the shape of the motion primitives remains very similar, and the same applies for the phase. There are small differences in terms of amplitude, especially in the case of the fifth component. The first four components, though, which are those that affect the joint trajectories the most, are almost the same. In addition, by observing the fifth component, it is also possible to notice that the main differences are those between WHS, and the two WHSB and WHS5, while WHSB and WHS5 are again almost identical. This means that the load didn't affect much the kinematics of the motion, but it only introduced a constraint on the arms motion, as also the empty box did.

### B. Trajectories Reconstruction

Basing on the analysis we performed and the results obtained we can state that human motion can be almost entirely described by kinematic Motion Primitives that are not changing among different people, and are not affected either by different walking velocities or slow running, or by the introduction of specific additional simple tasks/constraints on the arms motion as the holding of an object. This means that from these primitives we can generate different motions just by linearly combining them appropriately using the following formula:

$$\theta_i = \sum_{j=1}^n \alpha_{ij} \cdot p_j + m_i \quad (1)$$

where  $\theta_i$  with  $1 \leq i \leq 34$  are the joint trajectories,  $p_j$  with  $1 \leq j \leq 5$  are the primitives, and  $\alpha_{ij}$  is a matrix of scaling coefficients.  $m_i$  is the mean we have to add back on to the trajectories (remember that the PCA was applied on the zero-mean normalized trajectories). Using therefore only the first five components extracted, joint trajectories can be reconstructed with an accuracy of about 99%.

### III. HUMAN-LIKE WALKING BASED ON A RECONSTRUCTED COM TRAJECTORY

Following the study presented in the previous section, the primitive components obtained from the subjects were used to generate effective locomotion trajectories for a humanoid robot. In order to achieve this it was necessary to identify the scaling coefficients of (1). Since we didn't have the coefficients to reconstruct the trajectories from the average primitives, we decided to use the kinematic Motion Primitives extracted by one of the subjects when performing a WHS gait. In this case, it would be possible to obtain the coefficients to reconstruct the joint trajectories.

#### A. Method

However, as the kinematics of the robot itself is different from that of the person, the trajectory obtained could not be used directly in the robot. This is due to various mechanical constraints existing in the robot, mostly related to the robotic foot shape and construction, which could not for example permit a heel strike and tow off foot trajectory. As a joint to joint trajectory transfer would be not therefore a reasonable approach, we concentrated in this study on the reconstruction of the center of mass (CoM) trajectory, which is a function of the joint trajectories. We performed a PCA on the 34 joint trajectories plus the x,y,z CoM trajectories. The primitive components obtained were identical to those obtained when the x,y,z CoM trajectories were not considered. This is an expected result, as the CoM trajectories are in fact coupled to the joint trajectories. Using the primitive components, and the scaling coefficients obtained from one subject, we reconstruct the CoM trajectory. At that point we imposed to our robot to walk following the reconstructed CoM trajectory (scaled down, according to the dimensions of the robot). From the data we captured the gait phases could be extracted, and an engineered foot trajectory that satisfies them was generated. Using the reference CoM and feet trajectories, the joint trajectories to drive the robot were computed with inverse kinematics. In order to validate the trajectories we obtained, we tested them on our compliant humanoid robot, COMAN.

#### B. The experimental COmpliant huMANoid (COMAN)

The COMAN humanoid robot, Figure 5, is being developed within the AMARSI European project, which aims to achieve a qualitative jump toward rich motor behavior in robotic systems, rigorously following a systematic approach in which novel mechanical systems with passive compliance, control, and learning solutions will be integrated.

With regards to the mechanical systems with passive compliance the goal is [14]:

- to reduce the distinction between plant and controller, that is typical in traditional control engineering, to fully exploit complex body properties,

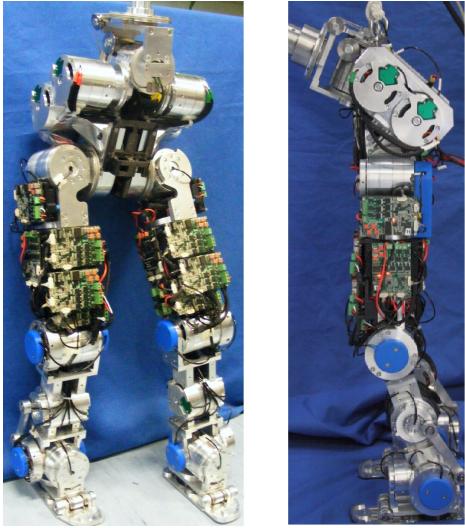


Fig. 5. The mechanical assembly of the COMAN lower body

- to simplify perception, control, and learning, and to explore how compliance can be exploited for safer human robot interaction, reduced energy consumption, simplified control, and faster and more aggressive learning.

The mechanical structure of a leg of the COMAN humanoid and an overview of its kinematics with the location of the D.O.F are illustrated in Figure 6. From the kinematic perspective the new lower body includes the lower torso (housing the waist module), and the two leg assemblies. The height of the COMAN lower body, from the foot to the waist, is 671 mm, with a maximum width and depth (at the hips) of 176 mm and 110 mm, respectively. The total lower body weight is 17.3 kg, with each leg weighing approximately 5.9 kg, and the waist section, including the hip flexion motors, weighing 5.5 kg.

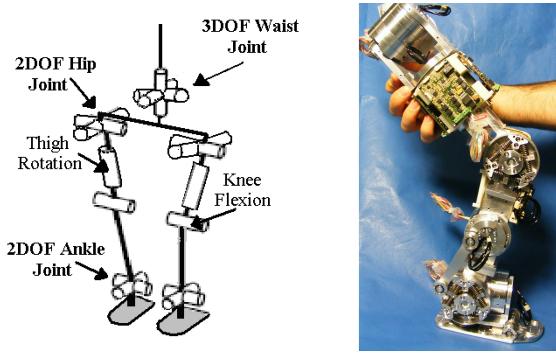


Fig. 6. The lower body kinematics and the compliant leg of COMAN

The leg of COMAN incorporates two series elastic (SEA) actuation units, which are placed at the knee flexion and the ankle dorsiflexion joints. The actuation structure used in the COMAN is based on a compliant actuation unit developed in [15]. To minimize dimensions while achieving high rotary stiffness, the compliant module of the unit is a mechanical structure consisting of a three spoke output component (Output

pulley, Figure 7), a circular input pulley, and six linear springs. More details on the actuator can be found in [15].

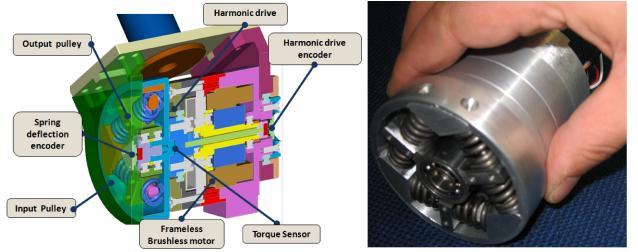


Fig. 7. The 3D CAD section and the physical prototype of the compact SEA module

Figure 8 shows the stiffness curve of the module within the range of the deflection angle for the compliant actuation unit used in the joints of the COMAN. The compliant joints have a passive deflection range of approximately 0.2 rad.

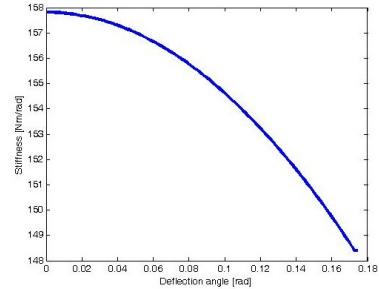


Fig. 8. The stiffness profile of the compliant actuation unit

### C. Results Obtained

Using the reconstructed CoM trajectories, COMAN successfully performed a stable, highly dynamic, human-like walking (in Figure 9 some snapshots from the video of the robot walking). A step was taken at every 0.56 s (gait cycle period = 1.12 s), with a resulting stepping frequency of 1.79 Hz (gait frequency = 0.89 Hz). This gait frequency was kept the same as in the original data obtained from the human subject.

What makes the robot walking really human-like was not only the CoM trajectory, that was of course different from the engineered trajectories usually obtained based on zero moment point criterion, but also the resulted knee trajectory (see the left knee trajectory in Figure 10 and in Figure 11): the knee straightens up to  $-5^\circ$  (bent knee has negative angle) around the toe off to push forward, and a second time right before the toe off of the opposite foot. This makes the gait of the robot look really human-like. The straightening of the knee was not imposed in any way, it was the results of following the imposed CoM trajectory.

A further consideration on the method adopted regards its flexibility. Using the kinematic Motion Primitives to reconstruct walking trajectories for robots permits to transfer the features of human walking to the robot without introducing any restriction to its gait. In fact, a good understanding of

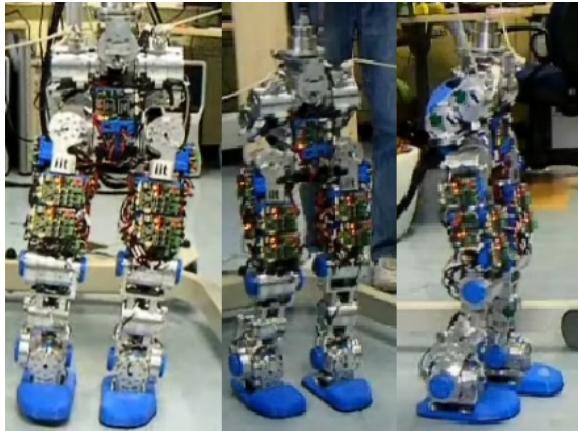


Fig. 9. Snapshots of the video recorded and showing COMAN walking with CoM reconstructed from kinematic Motion Primitives

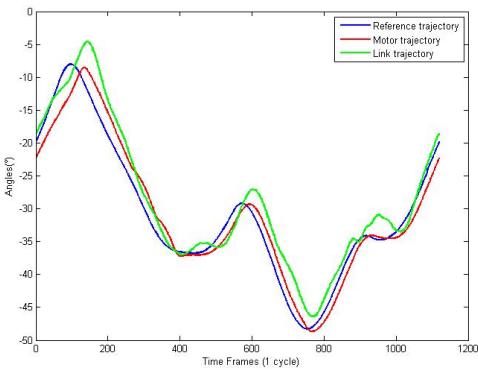


Fig. 10. Reference, motor side, and link side trajectories of the left knee (one gait cycle)

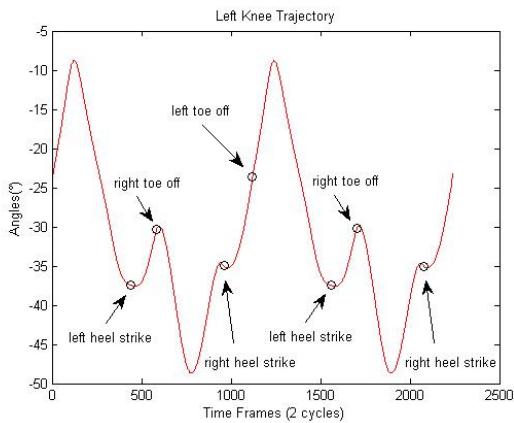


Fig. 11. Left knee trajectory (two gait cycles)

how to handle the coefficients in (1) would make it possible to generate different gaits, not constrained by the source human trajectories. This characteristic makes the method presented different from other method based on motion capture.

#### IV. CONSIDERATIONS ON ENERGY EFFICIENCY

Since the walking we obtained was highly dynamic, we examined the effect of scaling the gait frequency to the energy efficiency of the COMAN. The motivation for this was mainly triggered from the inherent compliance feature existed in the COMAN robot. In fact, because of the intrinsic compliance of the actuation system of the robot, it was expected that the tuning of the main frequencies of the gait, and the response of the mechanism to them can result in a more efficient walking. Hence, we performed the motion described in the previous section scaling the gait frequency in a range that goes from 0.5 Hz (stepping frequency = 1 Hz) to 1.25Hz (stepping frequency = 2.50 Hz).

The robot was able to successfully perform walking for all these frequencies. In Figure 12(a) you can see the overall energy consumption at the different gait frequencies in one second.

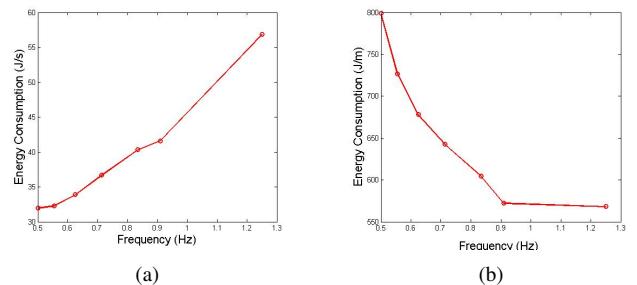


Fig. 12. Energy consumption at different gait frequencies (a) to walk for 1 s, and (b) to walk 1 m distance

However, this information is not much surprising: slow motions, in the same period of time, require less energy. At the same time, since the stepping frequency, and, consequently, the velocity of the robot are lower, in one second the robot is covering a smaller distance. It is then more useful to verify the energy required by the robot to cover the same distance at different gait frequencies. In Figure 12(b) you can see the energy required to walk 1 m, while in Table I all these data are summarized.

TABLE I  
ENERGY CONSUMPTION ANALYSIS

Gait Frequency (Hz)	Energy per second (J/s)	Energy per meter (J/m)
0.5	31.9737	799.3413
0.5556	32.2929	726.5891
0.625	33.9037	678.0740
0.7143	36.7244	642.6770
0.8333	40.3175	604.7617
0.9091	41.6235	572.3231
1.25	56.8241	568.2410

It can be seen that gait frequencies that are around 1 Hz (mechanism resonance frequency), required about the 70% of the energy necessary to cover the same distance at

lower frequencies. A reasonable interpretation to this result could be that, at higher frequencies, the robot could exploit the dynamics of the motion and the coupling with its own resonance frequencies, while at slower motions the gait became almost static.

## V. CONCLUSION

Synthesizing, a human-like walking for humanoid robots is desirable. At the same time this is not a trivial task to achieve, due to incompatibilities of the mechanical hardware, and to the high complexity of human walking motion itself. To address the latter we decided to perform a systematic analysis of human motion, and demonstrated how different gait of different people can all be reduced to a small set of kinematic Motion Primitives (kMPs). Hence, basing on these primitives, it is possible to reconstruct the joint trajectories corresponding to different gaits by properly choosing a set of scaling coefficients.

Due to the mechanical constraints and the differences between the robot and human kinematics, it is difficult to apply the reconstructed joint trajectories directly on a robot. Hence, we decided to exploit the coupling between joints and CoM trajectories, and reconstructed a human-like CoM trajectory from the kinematic Motion Primitives. We tested this trajectory on our compliant humanoid robot, COMAN successfully performed a stable, highly dynamic, human-like walking, with a stepping frequency of approximately 1.8 Hz, which was the same as the frequency of the original human gait.

Motivated by the inherent passive compliance of the robot the stepping frequency was subsequently regulated in order to investigate the effect on the energy consumption of the robot. With the gait frequency in the vicinity of one of the main resonance frequencies of the robot, the energy consumption was reduced to approximately 70% of what required to walk the same distance at lower frequencies.

A future work to extend the research presented in this paper will be focused on understanding more in depth the matrix of the components' scaling coefficients, and how to regulate its values to obtain gaits with different specific features. By doing so, it may allows to construct from human motion primitives robot joint trajectories which can be applied directly to the robot. A second research which deserves a more detailed analysis is the stepping frequency tuning. When performing highly dynamic walkings, like the one we obtained, an optimal frequency tuning can significantly reduce the energy consumption of the robot. This is one of the benefits of our humanoid robot, COMAN, resulting from the intrinsic compliance of its actuation system.

Further studies to understand the energy saving on the individual joints will also be performed.

## ACKNOWLEDGMENT

This work is supported by the European Commission FP7, AMARSI Project ICT-2009-4.

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