Simulation for the Optimal Design of a Biped Robot: Analysis of Energy Consumption

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Abstract. Our first aim is to develop a systematic method to estimate energy consumption of bipedal locomotion. This method is then used to evaluate the performance of materials and actuators that could be used for the design of a biped robot. Moreover, with this analysis we also demonstrated the importance of having good joint trajectories in order to reduce energy consumption. Results collected are then integrated with complementary information about materials and actuators, to finally suggest the best configurations. These indications are meant to be used for future developments of LARP, the biped of Politecnico di Milano. The method adopted, however, is general enough to produce valid results for any robot, and we hope our considerations will help in evaluating design choices for future humanoid robots.

Keywords: model of biped for locomotion simulation, computation of energy consumption, materials and actuators for the design of a robot

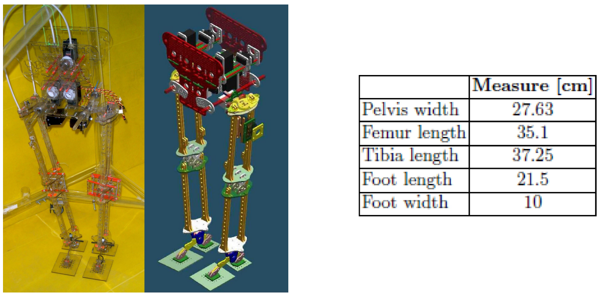
1 Introduction

Locomotion is an active research in humanoid robotics. To evaluate the performance of a walking robot the main features to consider are stability and energy-efficiency.

Our first aim is to design an energy-efficient robot. We based our research on LARP [1], the biped robot of Politecnico di Milano, and analyzed the energetic performance of different design solutions. In particular, we focused on the possible materials to use for the structure of the robot, and on the actuators. The results are meant to be used for the improvement of LARP itself, but are general enough to be a valid indication for the development of other humanoid robots.

In the last decade, research on bipedal locomotion has seriously enforced, and the performance of the robots have significantly increased. Among the most skilled robots, *Asimo* [2], produced by Honda, and *Wabian-2R* [3], from Waseda University, deserve a special mention. Asimo is 130 cm tall for 54 kg, and can walk at a speed of 2.7 km/h, or run at up to 6 km/h. Its 34 degrees of freedom, of which 6 in each leg, are actuated by servomotors. Its dynamic stability is guaranteed by a Zero Moment Point (ZMP) controller. Wabian-2R, whose height is 150 cm and weight with batteries is 64 kg, is the one that performs the most natural and human-like gait, with stretched knees and heel-contact and toe-off motion. These results are achieved by the use of a redundant mechanism with 2 degrees of freedom in the waist. Wabian-2R also has two 1 degree of freedom passive joints in its feet, that sum up with the other 39 active joints in the whole body, actuated by servomotors. ZMP is adopted to ensure stability. Last, in chronological order, is *Petman* [4], of the Boston Dynamics, supposed to be completed in 2011. It is the evolution of the famous BigDog [5], and the challenge is to obtain the same performance in the more difficult context of bipedal locomotion. Another problem concerns the actuators: BigDog is powered by a big combustion engine, which drives 12 hydraulic actuators. Petman, being smaller, will also need smaller motors.

The Light Adaptive-Reactive biPed, referred as *LARP* now on (Figure 1a), is the humanoid robot developed at DEI, Politecnico di Milano. Being focus on locomotion, it was decided to start building only the lower part of the robot. The structure is in polycarbonate, with some small parts in carbon-fiber. The reason of that choice was the good strength to weight ratio, as well as the fact that this material is way cheaper then others. The robot is 90 cm high, has 12 active degrees of freedom, 6 per leg, distributed in 3 in the hip, 1 in the knee, and 2 in the ankle, and 4 passive degrees of freedom, 2 in each foot, representing the heel and the toe. The target of building a light robot is completely satisfied, being LARP weight less then 5 kg. Moreover, dimensions, mass distribution, and range of motion of each joint reproduce those of an average human being. Currently LARP has 12 *HITEC HS-805BB* servomotors, that provide up to 24.7 kg cm torque each, located in the pelvis. A system of coramide tendons (with a tensile strength of 800 N, for a diameter of 0.5 mm) transmits the torques from the pelvis to the joints. The motors in this position keep high the center of mass of the robot, making it easier to correct the stability. On the other hand, friction generated by the transmission represents a big loss in terms of energy. To control the joint stiffness, each servomotor is equipped with a spring and a damper. A 3D model of the robot, developed in MSC Adams is also available (Figure 1b).



	Measure [cm]
Pelvis width	27.63
Femur length	35.1
Tibia length	37.25
Foot length	21.5
Foot width	10

Fig. 1. (a) Robot LARP, of DEI, Politecnico di Milano, (b) its model in MSC Adams, (c) and its dimensions

Two main features [6] characterize the mechanical design of LARP: the knee and the foot. The knee adopts a solution developed in advanced prosthesis, that use a multi-axial mechanism in which the center of rotation is not fixed, as in a pin joint, but moves along a trajectory that depends on the mechanism structure itself. The foot, whose design is a crucial phase to obtain stability and energetic efficiency, is composed by an arc and by 2 passive degrees of freedom, representing the heel and the toe. This solution permits to manage the energy received by the ground reaction force, and doesn't constrain the ankle in one fixed position.

2 Model of the Robot and Simulation

Our main goal is to develop a formal, reproducible method, not constrained by the specific characteristics of LARP, to determine the efficiency of certain configurations. The system architecture is represented in Figure 2. The first step is modelling the robot in a simulation environment. We decided to work in Matlab, exploiting the opportunities provided by the first version of the *Humanoid robots simulation platform* [7], now on referred to as *HRSP*, developed at the *Institute Mihailo Pupin*. We detected those parameters that affect the most the energetic performance of a robot, deciding, hence, to concentrate on the material used for the structure, and the actuators.

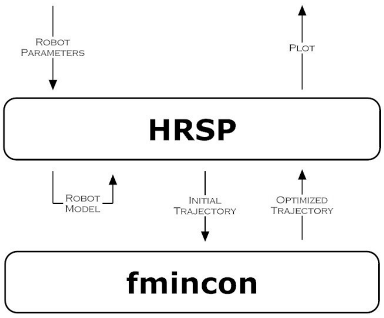


Fig. 2. Schema of the system developed to evaluate the energy efficiency of different design solutions

At this point, we needed a way to evaluate the performance of the different design solutions. That is, determine whether the robot is more efficient when a certain material and a certain kind of actuators are used, with respect with other possible solutions. The plan was to optimize the joint trajectories, and compare the energy consumption necessary to execute it in the different configurations. *fmincon*, a function provided with the *Optimization toolbox*, was the tool of choice.

2.1 The Model of the Robot

Using Denavit-Hartenberg notation with multiple kinematic chains we defined in HRSP the parametric model of a robot that reflects some characteristics of LARP. In this model we didn't reproduce the specific mechanics of the knee and the foot previously described: we just adopted a pin joint knee and a flat foot. The measures of the single parts, reported are in Figure 1c, as well as masses, center of gravity of each link, and inertia matrices, respect those of the real robot.

2.2 The Parameters

First decision to be taken is what material to use to build the structure, that is those parts that behave like bones for humans. The main features of the available materials are in Table 1. Candidate materials must satisfy certain requirements: be light, strong, and, possibly, not too expensive.

Table 1. Main characteristics of the materials considered for the structure of the robot

	Density [g/cm^2]	**Young's modulus [GPa]**	**Tensile strength [MPa]**	**Cost**
Polycarbonate	1.2	2	65	Low
Aluminium alloy	2.7	69	310	Medium
Titanium alloy	4.4	110	1000	High
Stainless steel	7.9	193	570	Medium

Polycarbonate, a thermoplastic material widely used in the engineering field, has a high strength to weight ratio, being its density only 1.2 g/cm^2, a restrained cost, and is easy to fabricate. Unfortunately, experience tells us this material is not strong enough to resist to impacts.

This is the reason why we decided to consider stronger materials. *Young's module* is the most used measure of the stiffness of an elastic material, while the *tensile strength* indicates the edge to pass from an elastic deformation to a plastic deformation. These mechanical parameters describe the performance of a material in terms of its strength. We focused our attention on three materials widely used in high-performance engineering applications.

Tempered 6061 aluminium alloy has a density of 2.7 g/cm^2, Young's modulus of 69 GPa, and tensile strength of 310 MPa. It contains magnesium and silicon as its major alloying elements, and is one of the most common alloys of aluminium. The high availability of raw material, aluminium is the most abundant metal in the Earth's crust, and the limited processing costs, due to its low melting point, make it an affordable solution.

Titanium 6Al-4V alloy, also known as titanium alloy grade 5, has a density of 4.4 g/cm^2, Young's modulus of 110 GPa, and tensile strength of 1000 MPa. It has a chemical composition of 6% aluminium, 4% vanadium, and remainder titanium, and is significantly stronger then pure titanium, while having the same

stiffness. Because of these properties it is the most commonly used titanium alloy. Compared to the aluminium alloy it has better mechanical features, though remaining light enough. It's main weakness is cost: both raw material and processing are expensive.
A more affordable material is the 316 stainless steel, a solid solution of iron with alloying elements, main of which are Cr, between 16% and 18%, and Ni, between 10% and 14%. It has a density of 7.9 g/cm^2, Young's modulus of 193 GPa, and tensile strength of 570 MPa. This means that its mechanical features are comparable or even better then those of the titanium 6Al-4V alloy, though its cost is way lower. Unfortunately this material is heavier then the others, and this would affect the weight of the robot and, consequently, its efficiency, with an incidence that we're going to evaluate with the method we developed.

A second parameter to study is what kind of actuators to use; this choice has a big impact on energy efficiency, in a way that is less predictable than in the materials case. In robotics the solution of servomotors is the most widely adopted. If the system is correctly set, an average efficiency of 80% can be reached. Some advanced robots are actuated by pneumatic or hydraulic linear actuators. These systems, however, are driven by auxiliary components, such as compressors or high pressure cylinders, that are heavy, noisy, and need a lot of space. This turns out to be a big limitation, that reduces the field of use to academics. A more sophisticated solution is given by EAPs actuators [8], polymers whose shape is modified when a voltage is applied to them. Interesting are the linear stack actuators based on dielectric EAPs, or multi-layer dielectric EAPs actuators [9]. The classical structure of dielectric EAPs, where a passive silicone or acrylic elastomer film is coated on both sides with electrodes, is replicated, stacking up several layers of this basic unit. This approach makes it possible to enlarge force and deformation in thickness direction, and, even more interesting, this kind of actuators, controlled by the applied voltage, behave in a way that is really similar to human muscles. This devices are extremely light, and can reach an average efficiency that is major than 90%. Of course, the use of linear actuators to drive rotational joints implies an additional loss, that depends also on the varying angle of the joint, and the simulation model we developed takes it into account.

2.3 The Optimization Module

Once developed a parametric simulation model of LARP in Matlab, we needed to define a way to evaluate the performance of the different solutions analyzed, in order to compare them.
We decided to use fmincon, provided by the Optimization toolbox, that finds the minimum of a constrained nonlinear multi-variable function, to determine which joint trajectories minimize the energy consumption for each material/actuator configuration. We used the active set algorithm [10], which is supposed to be best suited to our problem, and is one of the more efficient and accurate in the state of the art. The fmincon problem is specified in the following way:

$$\min_x f(x) \text{ such that } \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ A \cdot x \leq b \\ Aeq \cdot x = beq \\ lb \leq x \leq ub \end{cases}$$

where

x, b, beq, lb, ub : vectors;
A, Aeq : matrices;
$c(x), ceq(x)$: functions, possibly nonlinear, that return vectors;
$f(x)$: objective function, possibly nonlinear, that returns a scalar;

1. x is a vector containing the concatenation on joint angles at the different frames of a step, that is the minimal periodic sequence in bipedal walking.
2. $f(x)$, the objective function, is the evaluation of energy consumption to achieve one step, following a certain trajectory described by x. We started from the dynamic equation of motion: $H(q)\ddot{q} + C(q, \dot{q})\dot{q} + N(q) = \tau$, where H is the inertia matrix, C includes the Coriolis and centrifugal forces, and Gravity terms are included in the vector N. Velocity and acceleration vectors $\dot{q}$ and $\ddot{q}$ are the first order and the second order derivatives of the vector q, respectively. The mechanical energy is then computed as $M = \int_0^T \dot{q}^T \tau \, dt$. The efficiency of the different actuation solutions, and the additional losses given by linear actuators are then taken into account to evaluate the electrical energy E necessary to perform the desired trajectory. All of these equations are discretized to be used in Matlab.
3. It was then necessary to define the constraints the optimization problem must satisfy. With lb, lower bound, and ub, upper bound, the possible configurations of the joints are limited into a physical range. With the linear inequalities also velocity and acceleration of the joints are limited, while with the linear equalities the starting and the final position of the robot are fixed. The last constraint, defined with the nonlinear inequalities, is given by the ground, considered that during the swing phase the foot should avoid any contact with it.

This method, unfortunately, turned out to be computationally too complex. The length of vector x is equal to the number of joints multiplied by the number of frames in one step. Even if we set the time step to be long enough, obtaining only 50 frames per step, complexity remains too high. Some test, taking into account just one leg per time, that is 6 degrees of freedom, took months to get to a result. A complete simulation, with all the 12 degrees of freedom of the robot, would require fmincon to find the 600 values of a vector x that minimize the objective function, not violating any constraint, in an enormous solution space; this would mean, reasonably, years of simulation.

We investigated how to use distributed computing. Unfortunately, the basically sequential nature of fmincon makes it impossible to take advantage of parallelism, and makes it necessary to look for alternative solutions. We hypothesized that this alternative could be genetics algorithms: we substituted the fmincon function with the similar *ga* function, provided with the Genetic Algorithms toolbox, but results were not satisfactory. Given the high number of constraints, it takes a big initial population to just find a solution respecting all of them: setting a big initial population, on the other hand, makes the ga function even slower than fmincon. We also tried the optimization platform provided by *Tomlab*, but, again, the problem was too complex, and also this solution turned out to be not sufficient.

2.4 The Simplified Optimization Problem

At this point we approached the problem in a different way. We identified some simplifications that wouldn't affect the results we are looking for but reduce enough the complexity to allow fmincon process it in a reasonable time.

We respected a basic assumption: considered that this work aims to define whether certain changes in the LARP design can improve its efficiency, any approximation has to be conservative with respect to the current LARP configuration. The simplifications we adopted are, in a certain way, penalizing the choice of EAPs: thus, in case we obtain that, from our simplified model, they require less energy to perform the robot walking then servomotors, we're sure that, in the real system, their use would guarantee an enhancement that is equal or major then that reached in simulation. For this reason we decided to evaluate only the energy required to perform the swing phase of one leg, with fixed pelvis, when the robot is performing a rectilinear walking. Taking into consideration only one leg per time reduces the degrees of freedom to 6. The weight of the leg depends mainly on the material while the choice of actuators doesn't really affect it. On the contrary, using EAPs definitely reduces the weight of the pelvis. The energy required by the 6 degrees of freedom we're not considering, then, will be higher in the servomotors case. Moreover, the fact that we decided to set the robot walking trajectory as rectilinear makes it superfluous to evaluate all of the 6 degrees of freedom in the swinging leg: most of the work will be done in the sagittal plane, as in the case of planar robots. We can then just consider the 3 degrees of freedom, 1 one in the hip, 1 in the knee, and 1 in the ankle, that permit the motion of the leg in this plane, and reduce the length of vector x to 150. The last approximation is in modelling the linear actuators: for each joint, we set the two application points at the same distance from the joint itself. This solution is not meant to be the best possible, but reduces the weight of the calculation of energy consumption, further reducing the computational complexity.

These approximations provided a model whose energetic performance could be evaluated by the fmincon function in a reasonable time: every simulation took 10 to 14 hours, and we had the results of the 8 possible combinations of the 4 materials and the 2 actuators.

Fmincon, by the way, doesn't guarantee global optimality: in complex problems, as ours is, it is quite typical that the solution found is only a local minimum. However, improvements from the starting point, whatever geometric joint trajectory you might adopt, are relevant; energy consumption with an optimized trajectory is even orders of magnitude less than the starting one. This, as we'll see in the next section, happens because the peaks of energy consumption are eliminated.

3 Experimental Results

We can finally report the results obtained on the simplified problem.
A first observation regards the local minima in the search for the optimal trajectory. Fmincon doesn't ensure results returned are globally optimal. We'll see in Section 3.1 how we handled this possible limitation. But before reporting the results, we introduce the notation adopted to identify the configurations. The actuators are numbered: *1* refers to servomotors, and *2* to EAPs actuators. An alphabetical letter is associated to the materials: *a* polycarbonate, *b* aluminium alloy, *c* titanium alloy, and *d* stainless steel. This means that when, for instance, we write 1a, we intend the current LARP configuration, with polycarbonate, and servomotors.

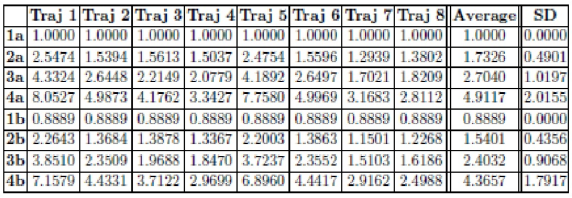
3.1 Energy-Efficiency of the Different Configurations

We performed 8 simulations, one for each configuration. All of them returned new joint trajectories and a value indicating the energy consumption. For the reasons explained in the previous section, these values are not directly comparable, because they may refer to different local minima. Anyway, the trajectories found are way more efficient than the starting one. Hence, we have a pool of 8 good trajectories, and we calculated the energy consumption for the different configurations for all of them. Since these values account only the energy necessary to move the swinging leg in the single support phase, absolute values are not actually significant. We are interested in the ratio between the different configurations, and in particular the ratio between current LARP configuration and the other analyzed. Results are reported in Figure 3.

It is interesting that in the single trajectories the ranking of the performance of the different configurations doesn't change: in particular, the order is always 1b, 1a, 2b, 2a, 3b, 3a, 4b, 4a. What changes a lot, instead, is how much these parameters influence the performance in the different trajectories. It turns out that in some of these, as for instance trajectory 7, using different configurations doesn't affect to much the efficiency. In some others, as trajectory 1, the influence of the choice of the parameters is clearer. This explains the high standard deviation observed.

From Figure 3a, we also noticed that the ratio between the performance of configurations 1a and 1b is constant. Whatever trajectory you consider, configuration 1b has an energy consumption that is 0.8889 of that of configuration

1a. We verified that also the 2b/2a ratio, as well as 3b/3a and 4b/4a, is 0.8889. This means that, fixed the material, the use of EAPs reduces energy consumption, that then will be around the 89% of that of servomotors. This percentage, furthermore, is an upper bound: it's important to remember that all of the approximations adopted to model our robot are penalizing EAPs. Anyway, this observation tells us that the influence of the actuators on the energetic performance does not depend on the material of the structure, and vice versa. Hence, we can continue our analysis of the effects of the choice of parameters, considering them independently.



	Traj 1	**Traj 2**	**Traj 3**	**Traj 4**	**Traj 5**	**Traj 6**	**Traj 7**	**Traj 8**	**Average**	**SD**
1a	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000
2a	2.5474	1.5394	1.5613	1.5037	2.4754	1.5596	1.2939	1.3802	1.7326	0.4901
3a	4.3324	2.6448	2.2149	2.0779	4.1892	2.6497	1.7021	1.8209	2.7040	1.0197
4a	8.0527	4.9873	4.1762	3.3427	7.7580	4.9969	3.1683	2.8112	4.9117	2.0155
1b	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.0000
2b	2.2643	1.3684	1.3878	1.3367	2.2003	1.3863	1.1501	1.2268	1.5401	0.4356
3b	3.8510	2.3509	1.9688	1.8470	3.7237	2.3552	1.5103	1.6186	2.4032	0.9068
4b	7.1579	4.4331	3.7122	2.9699	6.8960	4.4417	2.9162	2.4988	4.3657	1.7917

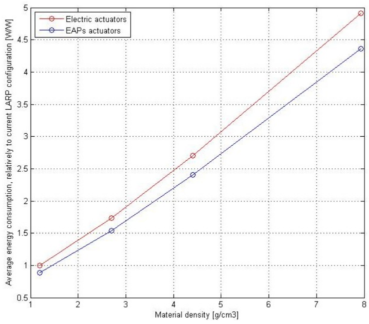


Fig. 3. Energy consumption, relatively to current LARP configuration, (a) in the different trajectories, (b) and graph of average values

About which material to use for the structure, we should avoid polycarbonate, because, though ligth, it is too fragile, and stainless steel, because too heavy and really inefficient.
The aluminium alloy and the titanium alloy are the most suitable materials: they're a good trade off between strength and efficiency. The choice between them depends mainly on the cost. The structural characteristics of the titanium alloy are definitely better. If this solution is not affordable, the aluminium alloy represents an absolutely valid, and more economic, alternative.

Choice on actuators is in a certain way simpler. In perspective, EAPs have a greater potential then servomotors. Being their structure similar to that of human muscles, the movement they produce is smoother and definitely more natural. They're also more efficient, as shown in the previous sections. But the fact that this is a young technology makes this solution more risky than servomotors.

3.2 Further Considerations upon the Optimization Module

As explained in the previous sections, the fmincon function doesn't guarantee global optimality. Theoretically, this would represent a serious limitation. Experimental data, instead, reveal the goodness of the method we adopted. We checked the energy consumption before and after optimization, for all of the eight simulations, and found that there is a consistent improvement of the performance. On average, the optimized trajectories require only the 1.97% of the energy necessary to perform the initial trajectory. In the best case this percentage decreases to 0.65%, in the worst it is 3.61%.

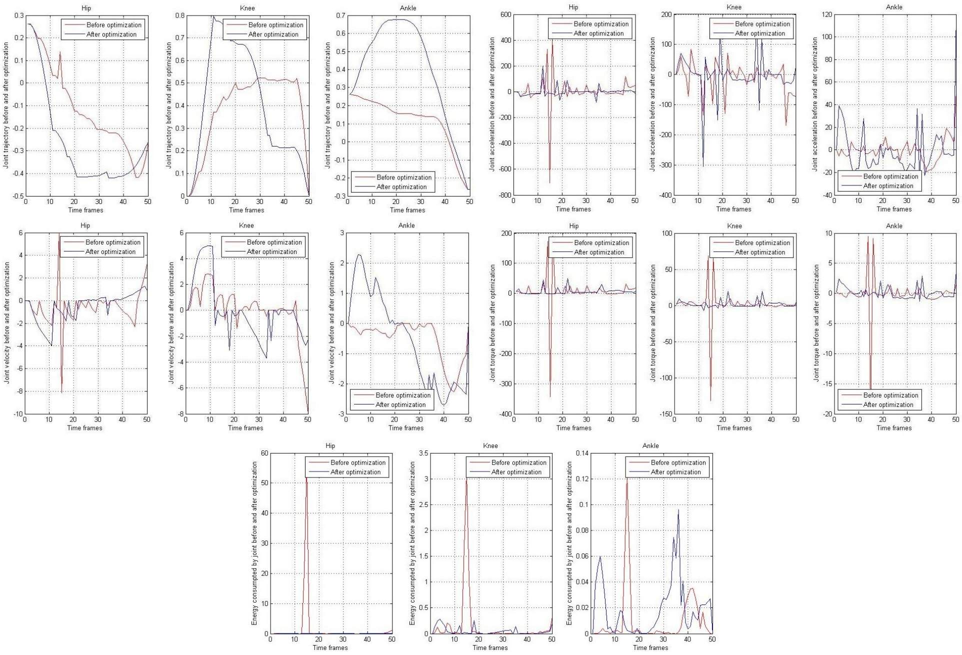


Fig. 4. Comparison of joint (a: top left) trajectories, (b: middle left) velocities, (c: top right) accelerations, (d: middle right) torques, and (e: bottom) energy consumptions (note that the y-axis have different scales) before (red) and after (blue) optimization

We discuss the simulation of the current LARP. Figure 4 represents the comparison of (a) the trajectory of the joints, of (b) their velocity, of (c) their acceleration, and of (d) the torques required, before and after the optimization. Just looking at the trajectories, it's not easy to understand why their performance is so different. The velocity figure starts helping, but it is in the accelerations and in the torques figures that it becomes clear how the optimization produced smoother trajectories: the highest peaks in accelerations and torques are eliminated, in particular in the hip joint, that is the one that requires more energy to move. In Figure 4e we can see the energy consumption, frame by frame, for each joint. To eliminate the peak around frame 15, the new trajectory might require more energy at some other instants, but the consumption now remains approximatively constant, and the comprehensive result, on the complete step, is excellent.

To conclude, we considered the foot trajectory. The constraints we formulated didn't impose any particular condition on the gait, but its correctness, that is avoiding the contact with the ground while the leg is swinging, and fixing the joints configuration at the first and the last frames. It is interesting to notice how the returned trajectories generate a gait that really reminds the human one. The foot always remains closer to the ground than with the original trajectory, and the movements are smoother and look a lot more natural. This could also be considered as a confirmation of how energy efficiency is one of the main goals in the human gait.

4 Conclusions and Future Work

Energy optimization is one of the most important objectives of research in autonomous robotics, that need to reach a certain degree of independence from human intervention for a reasonable time.

We have seen how dramatically the definition of the gait influences the energetic performance. Our interpretation of the goodness of our results is that the approach we proposed to generate trajectories itself is different. Usually, trajectories of the end-effector (in this case the foot) are imposed to follow a certain geometric shape. Joints trajectories are then obtained from the foot trajectory using inverse kinematics. These joints trajectories may result to be not smooth at all, and this generates the peaks of energy consumption we've shown in Figure 4e. Our method, instead, imposes only the correctness of the foot trajectory. Attention is then focused on the joints. The contribution of every single joint to the overall energy consumption is decisive for the choice of the trajectory. This approach has proved to be effective, and results obtained exceed expectations. It is also important to notice that the choice of using a very simplified simulation system permitted us to focus only on those parameters we are considering, sure that results are not affected by any other. This wouldn't have been possible if we decided to make use of a more precise, yet complex, 3D simulator. Moreover, the use of the fmincon function has an advantage: it works completely independently from the context of robotics, unaware of the fact that what it is optimizing are joint trajectories. This means that the results we got cannot be affected by a priori considerations. Returned trajectories, though, really remind those adopted in human locomotion, definitely more than the geometric trajectories generated on the basis of theoretical assumptions. This represents an important validation to the results we obtained.

About what material to use for the structure of the robot, as we've seen, there are two solutions that satisfy all the requirements: the tempered 6061 aluminium alloy, and the titanium 6Al-4V alloy. It is possible to achieve a further considerable improvement in the energetic performance of the robot by adopting more sophisticated solutions for the design of the joints, as done for the knee and the foot in LARP, or for the waist in Wabian-2R. About the actuators, a safe solution, for now, is represented by the more consolidated servomotors. In this case, it also becomes important to decide where to locate them. In LARP they have been included in the pelvis structure. If the robot was completed with an upper body, though, it would be possible to locate servomotors closer to the joints they actuate, and reduce the energy loss caused by friction, maintaining also a mass distribution similar to that of human body. Furthermore, the development of an upper body would improve even more energy efficiency. Although we usually associate arms with manipulation, they also play an important role in human walking. For instance they are used to counteract the rotation of the pelvis. It could then be interesting to think about a whole-body posture control, to reproduce also the way humans maintain stability. In fact, to manage external disturbances, we don't only modify the characteristics of our gait, as the length and width of our steps, but we also change the trunk inclination, and use arms to balance.

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