Optimisation of mono-articular or bi-articular linear actuation for a planar biped robot

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I. INTRODUCTION

Biped motions such as walking, running and jumping are very demanding on the motors [1], [2]. Choosing suitable motors is therefore of primary importance. In current biped designs, rotary motors are often used because their technology is well known. Recent advances in mechatronics have given rise to high-performance linear electric direct drive motors. An interesting feature of linear electric direct drive motors is their inherent backdrivability, which is due to the absence of gear reducer. Backdrivability has many advantages such as natural low impedance and the possibility to absorb the effects of high impacts [3], [4].

This paper is devoted to the design of biped legs actuated with linear motors. This actuation scheme is closer to the efficient muscular system of human legs. However, the efficiency of linear motors is highly sensitive to the placement of their attachment points. Both mono-articular and bi-articular motors are considered. Two main issues are addressed; (i) the best actuation scheme of the leg with three motors and (ii) the optimal placement of the motors on the leg. Eight leg architectures, shown in figure 1, combining mono-articular and bi-articular motors are investigated for walking and squat motion, mixing mono-articular and bi-articular linear actuators.

II. POSITION OF THE DESIGN PROBLEM

A methodology is proposed to optimize the linear motors attachment points. The mass distribution of the bodies was assumed to be constant regardless of the position of the actuators. Although not fully realistic from the point of view of bipedal design, this choice allowed us to better understand the motor placement problem by decoupling it from the mass distribution. The design of the robot is based on a set of movements that the robot must be able to perform. Here we consider a walking movement composed of a support and transfer phase and a squat movement. For each leg, a set of articular movements is deduced from this, to which a set of torques to be produced is associated. Let us consider such a set:

$$D(t) = [t, q_a(t), q_k(t), q_h(t), \Gamma_a(t), \Gamma_k(t), \Gamma_h(t)]^\top.$$

where the index a corresponds to the ankle, k to the knee, and h to the hip.

The torque will be generated by the forces exerted by the linear actuators. The relationship between forces and torques depends, of course, on the type of actuator chosen. When all the possible motors are considered, the following general model is obtained [5]:

$$\Gamma = J(q_a, q_k, q_h)F \tag{1}$$

or, in more details:

$$\begin{bmatrix} \Gamma_a \\ \Gamma_k \\ \Gamma_h \end{bmatrix} = \begin{bmatrix} J_{a,a} & J_{a,ak} & 0 & 0 & 0 \\ 0 & J_{k,ak} & J_{k,k} & J_{k,kh} & 0 \\ 0 & 0 & 0 & J_{h,hk} & J_{h,h} \end{bmatrix} \begin{bmatrix} F_a \\ F_{ak} \\ F_k \\ F_{kh} \\ F_h \end{bmatrix}. \tag{2}$$

In this paper, only non-redundant actuation schemes are studied. Since each leg has three degrees of freedom, only three motors are considered. A proper actuation choice requires that matrix J be not structurally singular. The transmission ratio between the force produced by a linear motor and the torque transmitted by this latter is highly dependent on the joint configuration. Moreover, a transmission singularity always occurs in any joint displacement of more than 180°. For all the joints the displacement for the motion considered satisfy this limit.

Accordingly, only the following eight architectures have to be considered (see Fig. 1):

- full mono-articular actuation : (M_a, M_k, M_h) (architecture 1);
- one bi-articular motor and two mono-articular motors : (M_a, M_{ak}, M_h), (M_{ak}, M_k, M_h), (M_a, M_{kh}, M_h), (M_a, M_k, M_{kh}) (architectures 2, 3, 4, 5, resp.)
- two bi-articular motors and one mono-articular motor : (M_a, M_{ak}, M_{kh}), (M_{ak}, M_k, M_{kh}), (M_{ak}, M_{kh}, M_h) (architectures 6, 7, 8, resp.),

During the design phase, the motors are selected according to the maximum force they have to produce. The linear motors used in this study can produce positive and negative forces. For more simplicity, each motor force F_j is assumed bounded by the same value: F_M with $| F_j| \leq F_M$. The objective is therefore to find the placement of the motor attachment points that minimizes F_M for all the joint configurations and torques belonging to the desired trajectories $D(t)$. Bounds on the attachment area must be defined when conducting the optimization. These bounds are deduced from design and bio-inspiration considerations. The set of attachment is denoted by S. The optimization problem can be stated as follows. For a leg architecture composed of three actuators M_1, M_2, M_3 corresponding to one of the eight actuation schemes shown in figure

1, find the best attachment points $A_1, B_1, A_2, B_2, A_3, B_3$ that minimize the maximal forces required for each actuator. There exists many solutions that will produce the same maximal force, thus we add a second term which is the minimization of the integral of the squared norm of F. This allows us to reduce also the loss of energy by joule effects in the motors.

$$\mathcal{C} = \min_{(A_1,B_1,A_2,B_2,A_3,B_3)\in S} \begin{pmatrix} \max(|F_1|,|F_2|,|F_3|)+ \\ \mu \int_{t\in D}(F_1^2+F_2^2+F_3^2)\mathrm{d}t \end{pmatrix} \tag{3}$$

such that

$$\begin{gathered} \forall t, q_a(t), q_k(t), q_h(t), \Gamma_a(t), \Gamma_k(t), \Gamma_h(t) \in D(t), \\ \begin{bmatrix} \Gamma_a \\ \Gamma_k \\ \Gamma_h \end{bmatrix} = J(q_a, q_k, q_h) \begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} \end{gathered} \tag{4}$$

III. COMPARISON OF SEVERAL DESIGNS WITH THREE MOTORS

The eight designs shown in figure 1 were optimized. In order to allow a placement of the actuator as close as possible to the trunk, the constraints on the motor attachment points are the following :

- For the distal attachment point, a disc of 0.1 m around the joint is considered.
- For mono-articular motors, the proximal attachment point is aligned with the axis of the body at a distance between 0 and 0.4 m to the joint center.
- For bi-articular motors, a disc of radius 0.1 m around the joint center is considered for the proximal attachment point.

The results are summarized in Fig. 2 and 3. The maximum transmission ratio is limited by the smallest distance of the attachment points to the joint center for mono- or bi-articular motors. This means that if a joint is operated by only one motor, the optimal design yields a motor force equal to the desired maximum torque divided by the maximum lever arm.

Disc-shaped attachment point areas were chosen for this study. The optimal solution for mono-articular actuation and for at least one attachment point of bi-articular actuator is to place the attachment point on the limit of the area.

A. *Best design*

The best design found is a (M_a, M_{ak}, M_{kh}), namely with two bi-articular motors for ankle-knee and knee-hip along with a mono articular motor for the ankle. This result is quite consistent with the study on humans. Indeed, it was shown in [6] that the mono-articular ankle muscle and the bi-articular muscle ankle-knee belongs to the most actives muscles for walking. The optimal design obtained is shown in the figure 4.

IV. CONCLUSIONS

Linear motors are becoming more and more efficient, are inherently backdrivable and allow for bi-articular actuation. In this context they become interesting to realize compact and bio-inspired bipedal robots. However, the efficiency of linear

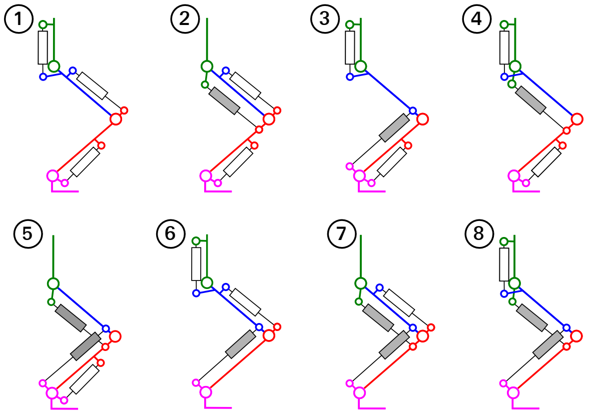

Fig. 1. The eight possible actuation schemes for one leg of the robot. The two attachment points of any mono-articular (resp. bi-articular) motors are separated by one (resp. two) joints. Attachment points were depicted with the same color as their respective anchor body. The mono-articular motors are shown in white, while the bi-articular ones are shown in grey.

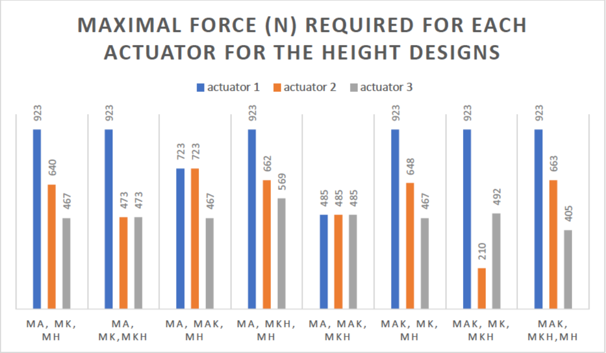

Fig. 2. Comparison of the height designs with respect to the maximal force to be produced by the actuators

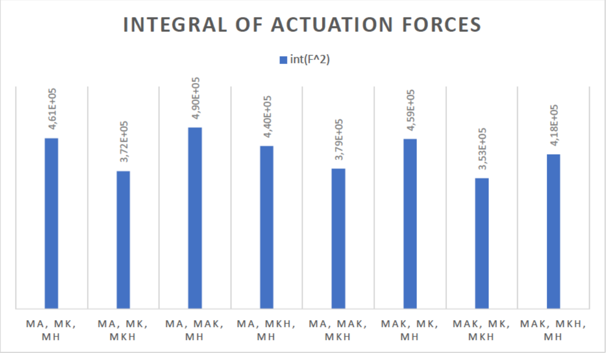

Fig. 3. Comparison of the height designs with respect to the criterion $\int_{t\in D}(F_1^2+F_2^2+F_3^2)\mathrm{d}t$

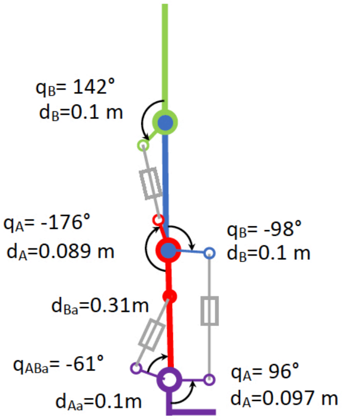

Fig. 4. The optimal design among the 8 architectures tested.

motors is very sensitive to the placement of their attachment points. A methodology has been proposed to optimize the linear motors attachment points. Since the transmission ratio of a linear motor depends on the joint configurations, a first step was to choose the movements that the biped must be able to perform: joint configurations and joint torques in particular were the input data of the design problem at hand. Both mono-articular and bi-articular motors have been considered. Results have pointed out the interest of using bi-articular motors to reduce the maximum effort required for each motor. An extension of this work is to take into account actuation redundancy.

REFERENCES

[1] G. Oort, R. Reinink, and S. Stramigioli, "New ankle actuation mechanism for humanoid robot," in *Proc. of IFAC World Congress (IFAC'11)*, Milano, Italy, August 28-September, 2011, pp. 8082–8088.

[2] K. Hosoda, T. Takuma, A. Nakamoto, and S. Hayashi, "Biped robot design powered by antagonistic pneumatic actuators for multi-modal locomotion," *Robotics and Autonomous Systems*, vol. 56, pp. 46–53, 2008.

[3] H. Kaminaga, T. Amari, Y. Katayama, J. Ono, Y. Shimoyama, and Y. Nakamura, "Development of backdrivable hydraulic joint mechanism for knee joint of humanoid robots," in *Proc. of Int. Conf. on Robotics and Automation*, Kobe, JAPAN, May 12-17, 2009, pp. 1577–1582.

[4] T. Ishida and A. Takanishi, "A robot actuator development with high backdrivability," in *2006 IEEE Conference on Robotics, Automation and Mechatronics*, 2006.

[5] A. Nejadfard, S. Schütz, K. Mianowski, P. Vonwirth, and K. Berns, *Moment Arm Analysis of the Biarticular Actuators in Compliant Robotic Leg Carl.* Springer, Cham, 2018.

[6] T. Zielinska, J. Wang, W. Ge, and l. Lyu, "Comparative study of muscles effort during gait phases for multi-muscle humanoids," in *Proc. of 12th Int. Workshop on Robot Motion and Control*, Poland, July 8-10, 2019.