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OPTIMIZED DESIGN FOR THE KNEE STRUCTURE OF A HUMANOID ROBOT *

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ABSTRACT

The objective of this work is to design and to make a part of a humanoid robot, named HYDROÏD. The keynote is a development of a self-sufficient robot by minimizing energy inputs required for its activity. Currently humanoid robots have a power/weight ratio lower than human, as a consequence a limited autonomy. In this work we propose an innovative knee structure in order to reduce friction, and as a result, increase energy efficiency. In classic knee architectures, the rolling elements are balls in bearings with relatively small curvature radii. Here, the idea is to increase this curvature radius to minimize rolling friction. This new joint is realized by rolling between two pieces (femur and tibia) linked by ligaments, and thus get an architecture similar to that of a human knee. As such, the contact is made by rolling movement without sliding between two cylindrical surfaces with circular section, and for which we need find an innovative actuation mechanism. To take advantage of energy savings achieved, we must optimize the mass distribution so as to achieve the smallest global inertia of the mechanical system. In this work we propose various technological solutions for actuation mechanisms. A comparative study is performed between the different technological choices for actuator (cylinder or rotary actuator) and for transmission (connecting crank arm, belt, gearing, etc.). Of course, this new structure must be in accordance with specifications for the knee about size and weight, as well as amplitude and speed rotation of joint. In this work, our choice is to use electric actuators. These different solutions are evaluated according several criteria such as inertial characteristic (mass and inertia matrix), overall size, energy efficiency and the complexity of the system (number of used pieces). Initially, solutions with pulley and belt or rotary actuators and cables seem to have best performance those other systems with connecting crank arm or gearing. Results should be confirmed from a more accurate determination of transmission efficiency. For prospect, the future works will be about optimization of pieces geometry, and in particular as study the gain due to using curvilinear surfaces with elliptic section. Calculation of stresses in the materials by finite elements will provide more information about optimization of di-

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mensions and shapes. Ultimately, energetic gains obtained with this architecture should be confirm through experimental tests.

INTRODUCTION

The main interest of technological evolution is to involve the performance of a technical system or machine and/or to realize it for a lower price. In the field of robotics, several studies have been carried out and important progress has been made in the last 30 years thanks to the development of humanoids [1]. Robots displayed more "intelligence" and their interaction with humans in daily life increased. The motivation for building biped robots appears in many fields, in particular the replacement of humans for hazardous tasks in areas containing obstacles or risks (activity in contaminated area, military interventions, etc.). The interest for using humanoid robots also arises from other diverse domains, like prosthesis design for disabled person or daily assistance of people with reduced mobility [2].

Currently, most humanoid robots use ordinary revolute joint for knee joint. Examples of such type of robots are numerous and famous, e.g. the robot HRP-2 [3] has a total of 30 DOF, a anthropomorphic design of the leg that allows one leg to be put in front of the other. Another well known robot is ASIMO [4] that can adjust the length of its steps, body position, speed and the stepping direction, in order to adapt to its moving environment. Some designers developed biped robots with more complex knee joints with an additional DOF using two revolute joint with orthogonal axes. In this category of robot, one can find the robot LOLA from Technical University of Munich [5]. This humanoid robot has a height of 1.80 m and a weight of 55 kg. Its physical dimensions are based on anthropometric data. The distinguishing characteristics of LOLA are the redundant kinematic structure with 7-DOF legs, an extremely lightweight design and a modular joint design using brushless motors.

The biggest challenge in these humanoid robot projects is building a robot that can provide high power for their tasks with a great autonomy [6, 7]. Currently humanoid robots have a power/weight ratio lower than human, as a consequence a limited autonomy. In order to resolve this problem, the energy efficiency of actuators must be improved and the amount energy used by the robot for its tasks must be reduced [8].

The knee is one of the most important and complex joint of human anatomy. The knee joint is essential for walking and allows different rotation movements. The main movement is a rotation about its horizontal axis, with a magnitude of 120° to 150° for bending angle and around 10° for hyperextension. Moreover, the knee enables small medial and lateral rotation movements. The knee ensures for a large part the standing position and must develop significant efforts during motion. When building a biped robot, it is practically impossible to duplicate the complexities of the human knee. It is therefore necessary to simplify the joint architecture in order to ensure main movement of knee. The objective of our work is to develop a self-sufficient robot by minimizing energy inputs required for his activity. The study we present here is part of a 30-DOF humanoid robot, named HYDROID [9]. We propose an innovative structure for the knee in order to reduce friction, and as result, increase energy efficiency. On the basis of the benefits made, this architecture may then use for other joints if their operating mechanism is comparable. In classic knee architectures, the rolling elements are balls in bearing with relatively small curvature radii. Here, the idea is to increase this curvature radius to minimize rolling friction. Finally the contact is made by rolling movement without sliding between two surfaces with circular section. This new joint is realized by rolling between two pieces representing femur and tibia (see Figure 2). The different parts are linked by ligaments, one get thus architecture similar to that a human knee, see[1] Figure 1.

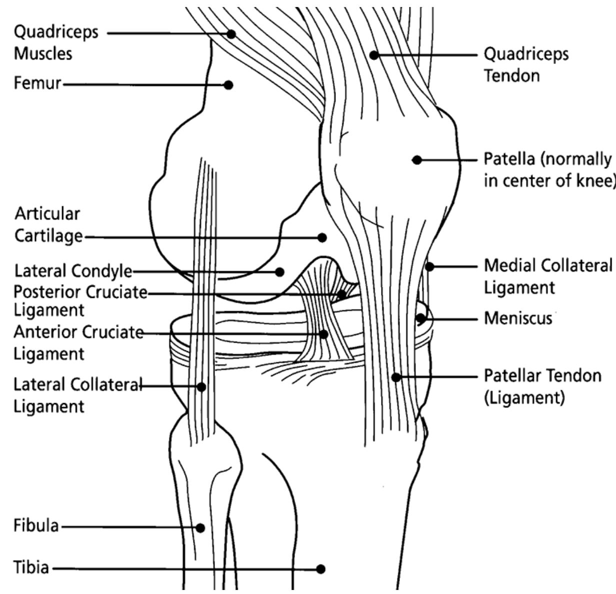

FIGURE 1. BONES AND LIGAMENTS OF A HUMAN KNEE.

The paper is organized as follows: the first part gives the kinematic model of the rolling knee structure, the second presents the sketch of the constrained DOF of the knee obtained by ligament and the third part discusses three designs solution of the motorized knee joint.

KINEMATIC MODELING OF THE KNEE WITH ROLLING CONTACT

The kinematics of the link is based on the rolling without slipping of a body (e.g. the femur) to another body (here the tibia). One body generally has six degrees of mobility with respect to the other. The rolling contact requires a non-slip in the

[1] http://en.wikipedia.org/wiki/Knee, version December 2011

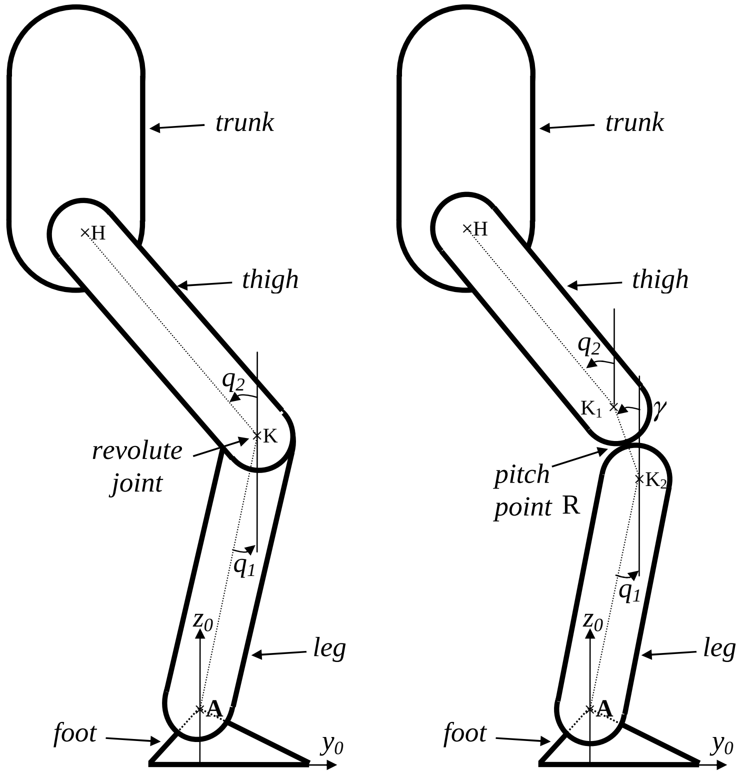

FIGURE 2. VIEW OF THE NEW KINEMATIC OF THE KNEE.

tangent plane which can be achieved by ligaments as the human knee. The degrees of freedom in rotation around the *y*-axis and *z*-axis (see Figure 2) are also blocked by the same ligaments. The line of contact between the tibia and femur is the rotation axis of the movement around the *x*-axis. The instantaneous center of rotation (ICR) thus moves along the profile of contact. When the profiles are circles as shown in Figure 2 (right view), the ICR is on the K_1K_2 line. If we consider only the motion of the hip of a biped robot staying on one leg, we have the following geometrical relations:

$$y_H = -(l_2 - r_2)\sin q_2 - l\sin\gamma_1 - (l_1 - r_1)\sin q_1 \quad (1)$$
$$z_H = (l_2 - r_2)\cos q_2 + l\cos\gamma_1 + (l_1 - r_1)\cos q_1 + h_p \quad (2)$$

with the angle of the rolling knee given by $\gamma_1 = \frac{r_1 q_1 + r_2 q_2}{r_1 + r_2}$ and the distances defined by $l_1 = AK$, $l_2 = HK$, $r_1 = RK_1$, $r_2 = RK_2$, $l_1 = KA$, $l_2 = KH$ and $l = r_1 + r_2$.

Assuming that the support foot does not slip on the floor, the coordinates of the velocity vector of the hip are given by the equations:

$$v_{Hy} = -(l_2 - r_2)\cos q_2\dot{q}_2 - l\cos\gamma_1\dot{\gamma}_1 - (l_1 - r_1)\cos q_1\dot{q}_1 \quad (3)$$
$$v_{Hz} = -(l_2 - r_2)\sin q_2\dot{q}_2 - l\sin\gamma_1\dot{\gamma}_1 - (l_1 - r_1)\sin q_1\dot{q}_1 \quad (4)$$

The rolling contact therefore provides an additional term in the expression of the forward speed which depends on the angle γ_1. As shown in [10], this difference in speed can improve the energy consumption criterion and therefore lead to a gain of autonomy.

SOLUTION FOR THE CONSTRAINED DOF OF THE KNEE

The solution adopted to restrict the degrees of freedom is shown in Figure 3. This solution is the same as that proposed in the works of [11] or [12]. The four ligaments placed in pairs on each side of the knee can restrict movement in the tangential directions of the contact and around the roll and yaw axes. The degree of freedom in direction normal to the contact plane is also constrained by the ligaments but in this direction the coefficient of stiffness due to the elasticity of the ligaments is the lowest. We therefore added springs for increased stiffness along the normal direction. The attachment points of these springs are placed in the center of each of the two cylinders that define the rolling surface. In this way, the springs do not affect the stiffness of the other degrees of freedom and do not exert torque around the actuated axis. Thereafter, it is intended to optimize the spring attachment points to further improve the energy transfer from the motor to the robot during walking.

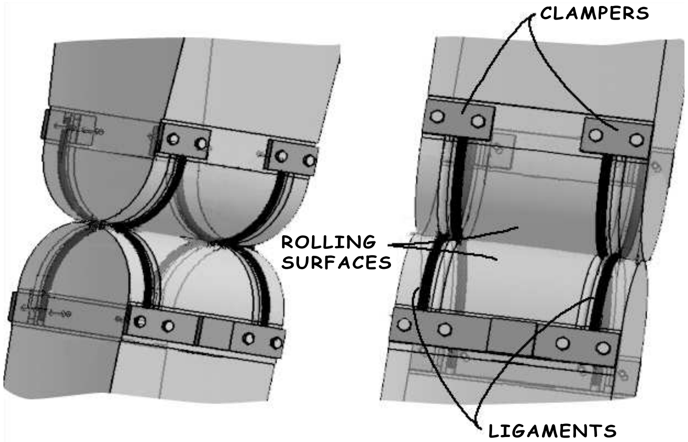

FIGURE 3. LIGAMENT PLACEMENT BETWEEN FEMUR AND TIBIA.

THREE CAD SOLUTIONS FOR THE ACTUATED KNEE JOINT

The design of a solution for a motorized knee joint is complex. The main design rules used to obtain a solution are:

- lead to the degree of freedom of the joint with the maximum efficiency and with minimal stress induced in the direction of freedom constrained by ligaments,
- place the motor and more generally all large masses as close to the hip joints,
- reduce the inertia of rotating parts,
- reduce the total mass of the entire design solution.

Three solutions are presented in the following. Two solutions use a rotary electric motor, the third solution uses a linear electric actuator. The second rule requires placing the actuators on the thigh. The kinematic motion transmission is done either by direct gear connection or by a transmission element with a lower stiffness (belt, cable). The decrease in stiffness may lead to less accurate positioning of the joint but can absorb the shocks of the robot's feet impact on the ground. The loss of precision in the joint can be compensated by the control law provided to a position sensor directly on the joint.

First solution with DC brushless motor and gearing

For this solution, a DC brushless motor is fixed inside the femur, see Figure 4. This has the advantage of balancing additional weight and inertia over the knee axis of the leg. An angle transmission allows transferring the rotary motion at bevel gears, which are positioned at each cylindrical section center. Two springs (not shown in Figure) lock the normal DOF along the z-axis.

The pattern shown here contains 121 pieces and requires 45 assembly operations. The structure has a total weight of $m_{total} = 11.7$ kg and the center of gravity is located at $z_G = 80$ mm over the contact line between femur and tibia. The system inertia matrix in kg.m^2 is given by:

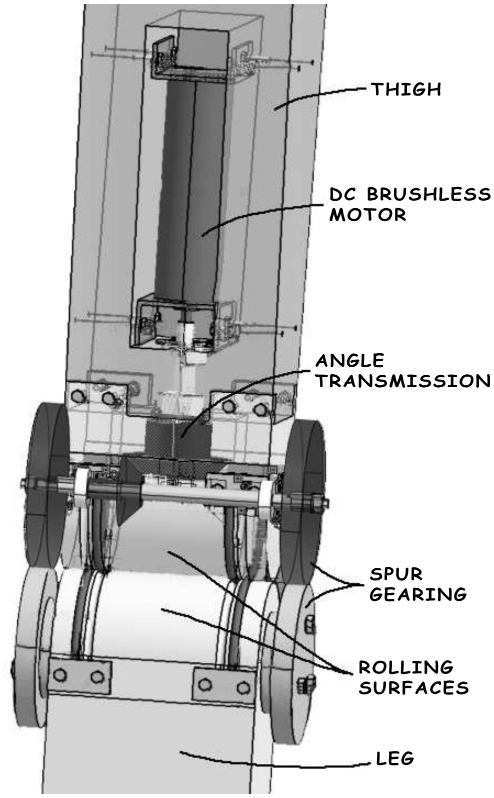

FIGURE 4. DESIGN WITH MOTOR AND GEARING.

$$I_S = \begin{pmatrix} 0.506 & 1.2\times10^{-5} & -3\times10^{-3} \\ 1.2\times10^{-5} & 0.505 & -8.2\times10^{-4} \\ -3\times10^{-3} & -8.2\times10^{-4} & 0.025 \end{pmatrix}$$

The actuation system has a weight of $m_{act} = 0.52$ kg. This structure is compact and the similarity with many existing systems may help benefit from knowledge developed. Power transmission can be made reversible by using appropriate gear technology. However there are several disadvantages, such as concentration of weight near to knee joint, which is harmful to respect the technical constraints. Of course, the motor will be positioned as high as possible in the thigh in order to reduce the inertia. In addition, the assembly of the bevel gear must be achieved with a high accuracy. The fact that axis of gearing, fixed on thigh and tibia, are each other moving can affect energy efficiency and walking fluidity. Moreover the external straight spur gearing, in addition to springs, increases global size of the actuation system.

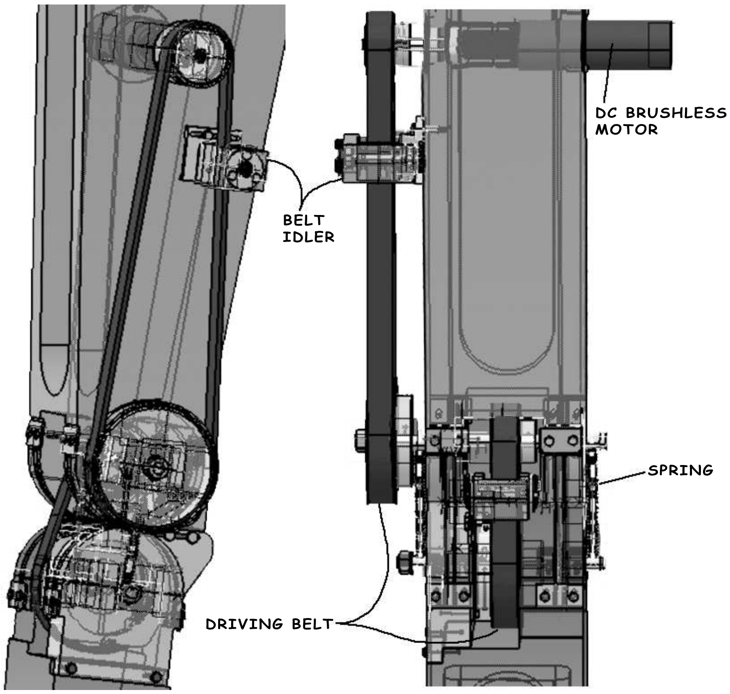

FIGURE 5. DESIGN WITH MOTOR AND TWO BELTS.

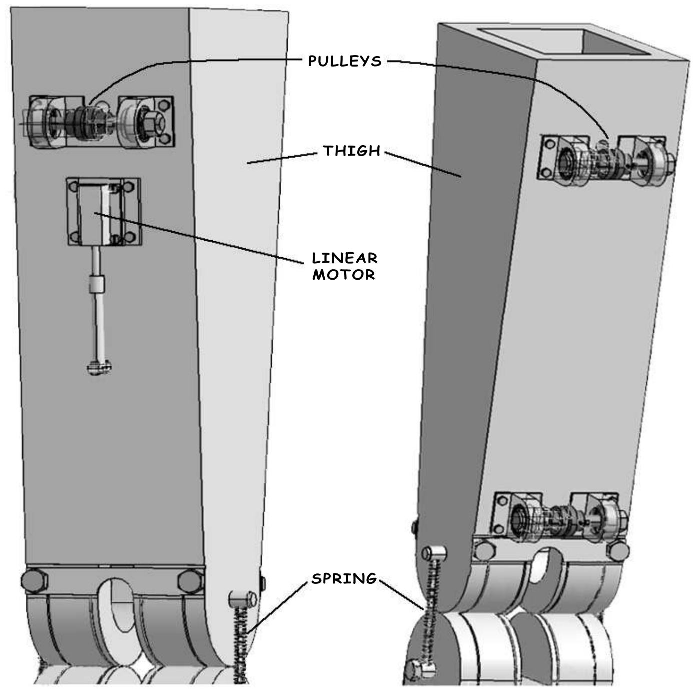

FIGURE 6. FIRST STRUCTURE WITH LINEAR MOTOR AND CABLES.

Second solution with DC brushless motor and belts

Alternatively with DC brushless motor is to use belts for the motion transmission, see Figure 5. A DC brushless motor is fixed on towards the top of the thigh, and a pulley and belt system sets a shaft in rotation. A second pulley and belt system, between femur and tibia, actuates the knee joint. The longitudinal DOF is locked with two springs. A grooving is made at the center of the rolling surfaces in order to rig up the second system belt system, reducing the global size of the actuation.

The structure is characterized by:

⋆ Assembly with 190 pieces (66 assembly operations)
⋆ Total mass $m_{total} = 11.2$ kg
⋆ Position of the center of gravity $z_G = 70$ mm

The system inertia matrix in kg.m^2 is:

$$I_S = \begin{pmatrix} 0.516 & -3.1\times10^{-5} & 5\times10^{-3} \\ -3.1\times10^{-5} & 0.511 & 0.01 \\ 5\times10^{-3} & 0.01 & 0.028 \end{pmatrix}$$

The actuation system has a weight of $m_{act} = 1.15$ kg.

The first advantage of this design is its involvement in locking the DOF about the leg axis, thus reducing thus loading of the spring connection. The assembly is well suited for our innovative joint design. The simplicity of the mechanism generates a relatively easy actuating control. The use of belt gives an opportunity to add an elastic element in the actuating system. Moreover, belt transmissions have relatively good energy efficiency and it is a quite reversible system. However, the use of two transmission stages damages the global efficiency. The relatively great size of the assembly is the major disadvantage for this design, and this requires a significant number of pieces and machining operations. Also, it is necessary to use belt tightened for adjustment of the stiffness, increasing complexity and weight.

Third solution with linear motor and cables

For this design, the actuator is a linear electric DC brushless motor driving with cables (not shown) through sheave pulleys, see Figure 6. Two structures are studied, one with a linear motor fixed on a face of femur and another where a linear motor is placed inside thigh, see Figure 7. The linear motor will be fixed as far as possible from the joint with the view to reduce the inertia. The system of cable and pulleys makes possible the joint actuation. In order to ensure contact between the rolling surfaces, two springs are added on the lateral sides. In the first case, the motor is positioned on the external surface of the thigh. Here, it is necessary to groove the rolling surfaces of limbs for routing of the cable. In the second technological solution, the linear motor is fixed inside a grooving of the thigh. This has the advantage of balancing weight and the global inertia of thigh, and also do not groove the rolling surfaces.

The external installation of the first structure is made with:

- ⋆ Assembly with 130 pieces (41 assembly operations)
- ⋆ Total mass $m_{total} = 8.0$ kg
- ⋆ Position of the center of gravity $z_G = 150$ mm

The system inertia matrix in kg.m^2 is:

$$I_S = \begin{pmatrix} 0.276 & -1.0\times10^{-5} & -2\times10^{-3} \\ -1.0\times10^{-5} & 0.279 & -2.8\times10^{-6} \\ -2\times10^{-3} & -2.8\times10^{-6} & 0.021 \end{pmatrix}$$

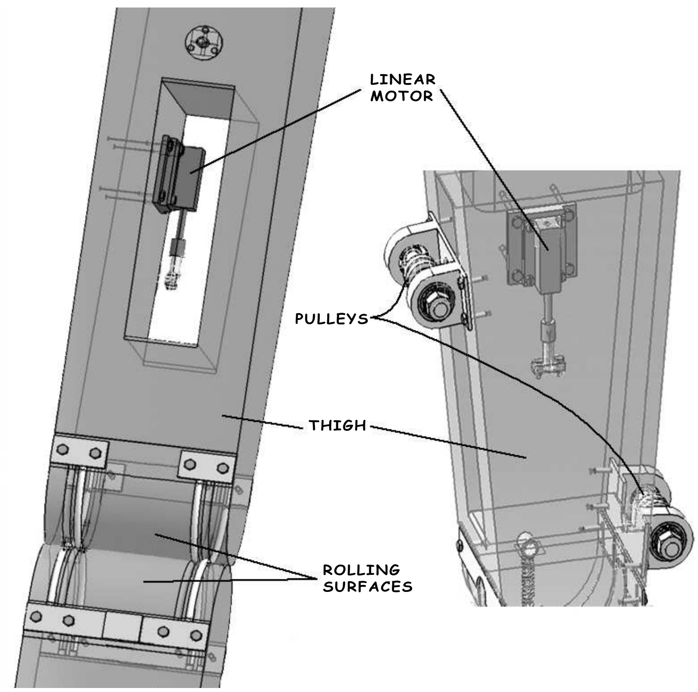

FIGURE 7. SECOND STRUCTURE WITH LINEAR MOTOR AND CABLES.

The external installation of the second structure is made with:

- ⋆ Assembly with 104 pieces (37 assembly operations)
- ⋆ Total mass $m_{total} = 8.0$ kg
- ⋆ Position of the center of gravity $z_G = 149$ mm

The system inertia matrix in kg.m^2 is:

$$I_S = \begin{pmatrix} 0.284 & -3.6\times10^{-7} & -2\times10^{-3} \\ -3.6\times10^{-7} & 0.284 & 3.5\times10^{-6} \\ -2\times10^{-3} & 3.5\times10^{-6} & 0.02 \end{pmatrix}$$

The assembly is relatively simple and flexible. It remains to identify the energy efficiency more accurately; however we can think that it is rather good. The weight distribution is very good because the distance between motor and knee joint is higher. The second design has the advantage that does not require a grooving on the rolling surfaces and also reduces the overall space needed for the assembly.

As a consequence of mechanism design, it is relatively more complex to control the position of the link.

COMPARISON BETWEEN THE THREE SOLUTIONS

These different solutions are evaluated according the main features discussed previously and several criteria as set out in Table 1. The complexity of the solution can be assessed by the number of parts needed to complete the assembly. The total mass of all parts (excluding the femur and tibia) of the joint are given in the third line. Parts femur and tibia are similar for different solutions and still need to be refined to minimize mass and moment of inertia. The fourth row of the table gives the position of the center of gravity of the assembly relative to the position of the axis of the ICR in the stand position of the robot.

The table clearly shows differences between the considered technological solutions. The transmission system by belt has a relatively great complexity and overall size, and it is obvious that designs using cables have an advantageous global inertia [13]. This is an essential characteristic to achieving a biped robot walking with agility. If classical combinations motor-gear or motor-belt fit industrial requirements (high precision and rigidity) it may not be the best to address humanoid robot requirements.

In Table 1 it appears that cable transmission systems have a lower weight, and a more remote center of gravity. This decrease of global inertia is not only a major contributing factor to achievement of a walking smoothly biped robot, but also it brings a higher power/mass ratio and a easier placement of actuators.

CONCLUSION

In this paper, we presented the most pertinent functional solutions in order to actuate the novel design of knee joint for humanoid robot. An initial comparison is made according to several assessment criteria, and can be used for futures studies that will focus on technological choices fewer in number but more accurately. Above all, the predominant selection criteria are the weight via inertia and the energy efficiency in order to take advantage of energy savings achieved with the new design of joint. As a first time, it would appear that the mechanical system with the linear motor and cable should be the best design among the technological choices explored in this work. The assembly has a reduced total weight because of a lower number of pieces used

Criteria	Design 1	Design 2	Design 3a	Design 3b
Complexity of the assembly	121 pieces	190 pieces	130 pieces	104 pieces
Size of the actuation	medium	relatively important	relatively small	relatively small
Total weight	11.7	11.2	8.0	8.0
Position of the center of gravity	79 mm	68 mm	150 mm	149 mm
Weight of joint	0.52 kg	1.15 kg	≈ 0.3 kg	≈ 0.3 kg

TABLE 1. COMPARISON OF THE DIFFERENT DESIGN SOLUTIONS

for transmission and actuation. Consequently, the structure inertia and the global size are lower. Of course, these needs to be confirmed through a more accurate study of the energy efficiency, and for which other technological system of actuation are not fully supplanted. For prospect, the future works will be about the optimization of pieces geometry. In particular, we will study the energy gain to using curvilinear contact surfaces with elliptic section. Calculation of stresses in the materials by finite elements will provide more information about optimization of dimensions and shapes. Ultimately, the energetic gain obtained with this innovative architecture should be confirmed through experimental tests. If this design is agreed, thus the new knee can be implemented on the humanoid robot HYDROÏD, and perhaps used for other joints.

ACKNOWLEDGMENT

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