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F-IVT Actuation System to Power Artificial Knee Joint

Alò Roberta, Bottiglione Francesco, Mantriota Giacomo

***Abstract*—**The efficiency of the actuation system of exoskeletons and active orthoses for lower limbs is a significant aspect of the design of such devices because it affects their efficacy. The F-IVT is an innovative actuation system to power artificial knee joint with energy recovery capabilities. Its key and non-conventional elements are a flywheel that acts as a mechanical energy storage system, and an Infinitely Variable Transmission (IVT). The design of the F-IVT can be optimized for a certain walking condition, resulting in a heavy reduction of both the electric energy consumption and of the electric peak power. In this work, by means of simulations of level ground walking at different speeds, it is demonstrated that the F-IVT is still an advantageous actuator which permits to save energy consumption and to downsize the electric motor even when it does not work in nominal conditions.

***Keywords*—**Active orthoses, actuators, lower extremity exoskeletons, knee joint.

I. Introduction

THE human locomotion dynamics would be very efficient because each leg joint requires both positive and negative power, giving the chance to recover energy [1], [2]. The actuation system of the lower extremity active orthoses and powered exoskeletons should exploit the human walking dynamic characteristics [3]-[5] by storing and releasing energy according to the instant value of the requested power of the joint, with the aim of improving its efficiency. That would reduce the energy consumption and the peak power of the motor [6], [7], permitting to enlarge the operating range and lighten the weight of whole system.

Exoskeletons are usually powered by electric machines [8], [9], because of their high efficiency [10]. However, even if the electric drives are reversible machines, energy recovery is not usually considered [11], [12], because of the relatively low efficiency of the mechanical to electrical energy conversion and of the battery charge/discharge process [3], [13].

Moreover, because the gait cycle frequency is some thousands cycles per hour, the batteries would be easily stressed to failure.

The use of springs has often been considered to recover energy [14], [15]. The Series Elastic Actuators (SEAs) are very interesting devices with elastic energy storage capabilities, where a spring is placed between the motor and the joint to store elastic energy in the negative power portions of the gait cycle and to release it subsequently [16]-[20], when necessary. This working principle permits to reduce the maximum motor torque and to adjust the speed regime of the motor [21]-[25]. On the other hand, the introduction of compliance does not permit to optimize the efficiency of the electric drive, which is asked to work over a wide range of speed and torque values. To overcome this problem, it has been noticed that a continuous transmission between the motor and the load, allows the motor to work at the most efficient condition [3]. The great drawback of SEAs is that they are passive systems that are actually convenient only for one given working condition, the one for which the spring is optimally tuned [7], [26].

A novel and very efficient actuation system to power artificial leg joints has been proposed in [27]. The system is named Flywheel-IVT actuator (F-IVT) and it is made of a brushless DC motor, a flywheel, an Infinitely Variable Transmission (IVT) and a harmonic drive gear (HD). The working principle of the F-IVT is similar to that of the mechanical KERS (Kinetic Energy Recovery System) for automotive applications [28], in which the flywheel stores energy (in form of kinetic energy) when the required power is negative and reuses it when the power is positive. The IVT transfers the kinetic energy from the flywheel to the joint and vice-versa, changing seamlessly the speed ratio from positive to negative values. Storing energy in the flywheel permits to reduce the energy consumption but also to downsize the electric motor, which has to provide an almost constant amount of power about equal to the mean value of the power required rather than to the maximum [27]. The authors have shown the benefits achieved with the F-IVT in two different designs, one optimized for walking at 1 m/s and the other one for running at 4 m/s [27]. In this paper we prove that the benefits of F-IVT with respect to a Direct Drive system remain also when the working conditions are far from those for which the system is optimized.

II. The F-IVT Actuation System

Human walking is a cyclic motion that starts and ends at two successive heel strikes of the same foot [6], [10] (Fig. 1). From the analysis of the power required in human walking, it results that it could be very efficient: the gait cycle involves both positive and negative power, giving the chance to recover energy [1], [2]. In some conditions, the negative power could be a considerable part, resulting in an overall negative amount of energy as, for example, in the knee joint. Thus, in ideal working conditions, no external source of power would be necessary to move the knee joint, and the motor should be turned into a brake [2], [27]. Of course, because of the power losses in the transmission devices occurring in real working conditions, the electric drive must provide some power, which can be minimized through an efficient design of the actuation

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system.

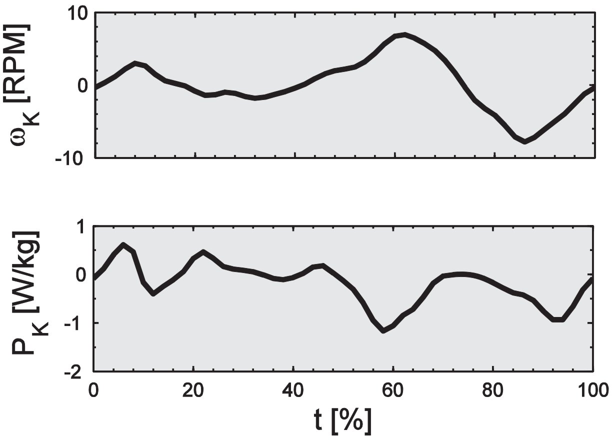

Fig. 1 Speed (ω_K) and power (P_K) requirements of the knee joint in level ground walking at the speed of 1.1 m/s [7]

The F-IVT is an innovative actuation system to power artificial leg joints [27], which permits to exploit the characteristics of the human walking dynamics. It includes a flywheel, an IVT, and a HD unit between a brushless DC motor and the knee joint (Fig. 2).

Its design move from the idea that, being human walking a cyclic motion for each joint, it can be studied as a periodic system in which a flywheel can be introduced to store kinetic energy. This requires that the speed ratio changes properly to move the kinetic energy from the flywheel to the knee joint when the joint power is positive and to return it back to the flywheel when negative power is demanded. Thus a continuous transmission is needed and, since the speed of leg joints ranges over positive and negative values (Fig. 1), an IVT is chosen:

$$\tau_{IVT} = \frac{\omega_K}{\tau_{HD}\,\omega_M} \tag{1}$$

where τ_{IVT} is the speed ratio of the IVT, ω_K is the angular speed of the knee joint, ω_M is the angular speed of the motor and τ_{HD} the speed ratio of the HD. The rate of change of τ_{IVT} (τ_{IVT}) is given by making the time derivative of (1):

$$\tau_{IVT} = \frac{\omega_K - \omega_M\tau_{IVT}\tau_{HD}}{\omega_M\tau_{HD}} \tag{2}$$

where ω_K is the angular acceleration of the knee joint.

The IVT continuously changes the speed ratio from positive to negative values according to the end-user requirements, permitting the motor to work at fixed operating point, at the most efficient condition. This latest aspect gives a great advantage in the mechanical systems where the IVTs are introduced, because it permits to cut off motor's consumptions and size [29]-[31]. In particular, exoskeletons would take advantage from this achievement, because it allows a larger operating range.

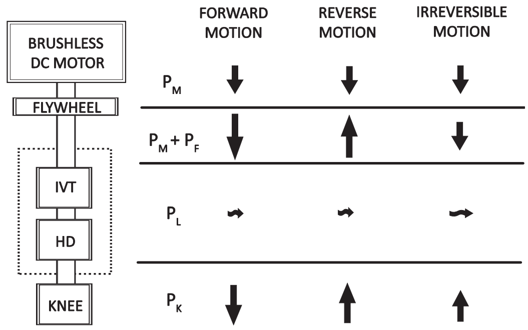

Fig. 2 Configuration of the actuation system proposed under direct, reverse and irreversible operating conditions. The arrows indicate the power flows direction in each of them [27]

III. Mathematical Model of the F-IVT

A mathematical model of the F-IVT was developed to estimate the performance of the whole system, examining the different modes under which it works.

The power balance equation of the system is:

$$P_M + P_F + P_L = P_K \tag{3}$$

where P_M is the motor power, P_K is the power demanded by the knee joint, P_L is the power lost in the transmission and P_F is the opposite of the rate of change of flywheel kinetic energy.

In F-IVT the motor is asked to provide an almost constant amount of power, close to the mean value of the power request of the joint that is by far smaller than the peak value. This is possible thanks to the flywheel that stabilizes the angular velocity of the motor and compensates the fluctuation of the requested power at the knee joint. The motor is supposed to provide a constant torque C_M, which can be calculated by:

$$C_M = \frac{1}{T\omega_M}\int_0^T P_M(t)\,dt \tag{4}$$

where T is the duration of the periodic gait cycle and ω_M is the mean value of the motor speed.

All the transmission devices of the F-IVT work under very changeable conditions, because both the speed and the torque of the knee joint spread over a wide range of values. Elsewhere the power flow direction changes: the system works under forward operation mode when the power flows from the flywheel to the joint and under reverse operation mode otherwise (Fig. 2). This obviously affects the instant efficiency value of each component of the F-IVT. Furthermore, the reverse mode is not always possible. We named this condition "irreversible". In this case (Fig. 2) both P_F and P_K are dissipated as heat losses. In the F-IVT actuator, the irreversibility of the motion can involve the HD, the IVT or both simultaneously, depending on the actual values of speed and torque.

We provided detailed efficiency models for all the elements of the transmission, considering all the possible directions of power flows.

Exoskeletons are usually powered by DC brushless motors. A typical brushless DC motor map, with the maximum efficiency of about 88% [3], has been adapted to match our requirements.

Different typologies of IVT have been developed along the years [32]-[36]. An IVT with shunted CVT architecture was considered in the F-IVT actuator, because mathematical models of its efficiency are well established in the literature [37]-[40]. The shunted CVT architecture of IVT is made of the following component devices: a micro-toroidal CVT (Continuously Variable Transmission), a micro-planetary gear train (PG) and a fixed speed ratio drive (FR).

We refer to [37] to model the efficiency of the IVT, considering all the operating modes of the transmissions i.e. the direct, the reverse mode and the conditions under which the IVT is irreversible. The τ_{IVT} range can be optimized to improve the global efficiency of the transmission. The efficiency of the IVT (η_{IVT}) is depicted in Fig. 3 as a function of τ_{IVT} in the selected ratio range, for both direct and reverse modes. The τ_{IVT} greatly affects the η_{IVT}, which decreases when the absolute value of the τ_{IVT} becomes small. Elsewhere, the IVT always works more efficiently in direct than in reverse mode, that is even not permitted (irreversibility) near the neutral gear condition.

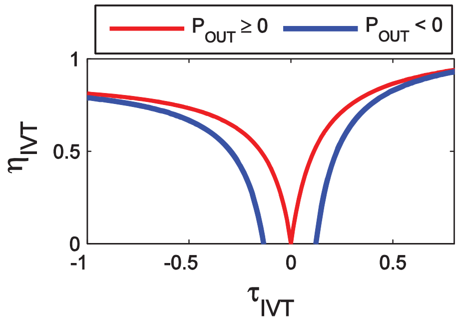

Fig. 3 Efficiency maps of the IVT in direct and reverse operating modes

HD gears are usually part of the actuation systems of exoskeletons because of the large torque capacity, high gear ratios and small size [10]. In the F-IVT system the HD is connected directly to the knee joint. The efficiency of HD depends mainly on the speed of the input shaft and on the torque of the output shaft [41], apart from their size, the temperature and the lubrication. Additionally, if proper values of torque and speed are not reached, HD gears do not permit the inversion of the power flow. The efficiency model of HD unit considers all these aspects following the guidelines given by the manufacturers of Harmonic Drive AG.

IV. Results

The model described above has been used to evaluate the performance of the F-IVT actuator under different walking regimes. A comparison with a traditional system, characterized by the direct coupling of the motor with the HD is also presented under the same operating conditions. We refer to this last configuration as Fixed Ratio Drive (FR-D) for brevity. In FR-D system, the electric recovery of energy was not considered, as commonly assumed in the literature [11], [13] for the reasons explained above.

Cycle gait analysis (CGA) data from [7] have been used to calculate the knee joint power requirements at different walking speeds (from 1.1 to 2.6 m/s). The whole system has been designed in such a way that it can power the knee joint over the full range of walking speed explored (Table I). In particular we would like to verify if the F-IVT system is still convenient when it does not work in nominal conditions.

TABLE I
Nominal Values of the Components of the Actuation System of the Exoskeletons in the Two Configurations Considered in This Work (F-IVT and FR-D)

		F-IVT	FR-D
Electric Motor	Nominal Speed [RPM]	6837	6647
	Nominal Torque [Nm]	0.040	1.547
Flywheel	Moment of Inertia [kg.m2]	$5\cdot10^{-4}$	-
IVT	τ_{IVT}	[-1, 1]	-
Harmonic Drive	τ_{HD}	1/80	1/80
	Nominal Torque [Nm]	25	25

The knee joint requires a negative amount of energy at each cycle for all the walking speeds, which goes from -0.18 J/Kg at the speed of 1.1 m/s to -0.45 J/kg at 2.6 m/s. However, because of the power losses in all the transmission devices of the F-IVT powertrain, the motor is asked to deliver a positive amount of power. Let us consider walking at 2.1 m/s as an example. The instant efficiency values of both IVT and HD gears change very much along the cycle (Fig. 4), being equal to values that are usually lower than the nominal, and that sometimes are even equal to zero or negative when the system is irreversible (only positive efficiency points are shown in Fig. 4). On the contrary, the motor efficiency is nearly constant and close to the nominal value of 88% (Fig. 4).

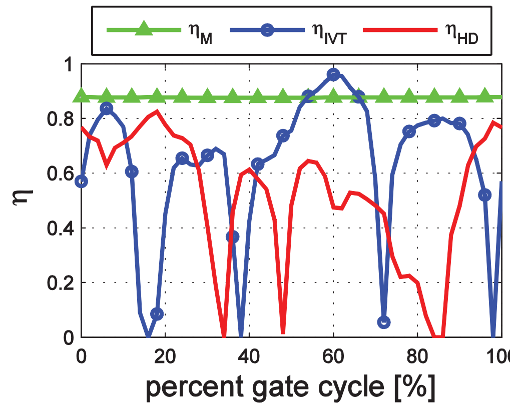

Fig. 4 Instant values of the efficiency of the motor, of the IVT and of the HD unit of F-IVT in level ground walking at 2.1 m/s

This means that the motor works nearly at fixed operating point, providing an almost constant amount of power (Fig. 5). On the other hand, the flywheel thanks to the IVT that properly changes the speed ratio (Fig. 5), follows the variation of the power of the knee joint (Fig. 6). Such a behavior makes the F-IVT more convenient than a FR-D system where the electric machine is forced to work under very changeable conditions. Similar results as those of Figs. 4-6, which are not shown for the sake of brevity, have been achieved for all the investigated walking speeds. The F-IVT actuation system permits to downsize the electric machine and to reduce its energy requirements per cycle at all the walking speeds considered (Table II). In particular the electric peak power is reduced by an average value of 88% over the range of walking speed explored. The greater reduction (-90%) is reached at the maximum walking speed considered (2.6 m/s), when the peak power demanded to the electric motor is about of 0.38 W/kg in a F-IVT system and of 3.65 W/kg in a FR-D system. The average value of the reduction in the electric energy requirement is of about 66%. The greater reduction (-67.63%) is here reached at the speed of 1.6 m/s, where the energy requested in a cycle changes between the values of 0.26 J/kg with F-IVT and of 0.81 J/kg with FR-D. This proves that the F-IVT is a flexible system able to efficiently power knee joint even if it does not work under the nominal conditions. It has been here estimated that both the peak of electric power and the electric energy consumption are always greatly reduced in the F-IVT system if it is compared to the FR-D whic operates at the same speed (Table II).

V. Conclusions

The F-IVT is an innovative actuation system to power artificial knee joints that includes a flywheel, an IVT and a HD unit between a brushless DC motor and the knee joint. It was proved that the F-IVT is more advantageous than a traditional actuation system where the motor is directly coupled to the joint through a HD gear. The F-IVT efficiently exploits the human locomotion dynamics permitting to recover energy and store it into the flywheel when the power demanded by the knee joint is negative.

The flywheel stabilizes the angular velocity of the motor and compensates the fluctuation of the requested power at the knee joint. As a consequence of this, the motor is asked to provide an almost constant amount of power, close to the mean value of the power request of the joint and by far less than the maximum. Thus, the F-IVT reduces the electric peak power, permitting to downsize the motor. Also the electric energy required in a cycle is greatly reduced. In this work it was proved that the F-IVT outperforms the FR-D system even if it is asked to work under operating conditions that are different from those for which the system works at its optimum. The system under investigation was designed for best walking at 2.6 m/s. Then, the performance of the F-IVT has been evaluated in walking at different walking speeds, from 1.1 to 2.6 m/s. It resulted that F-IVT powers efficiently the knee joint in all the walking regimes examined, reducing both the electric energy requirement per cycle, by an average value of the 66 %, and the electric peak power, by 88%, if compared to the commonly adopted Fixed Ratio Drive.

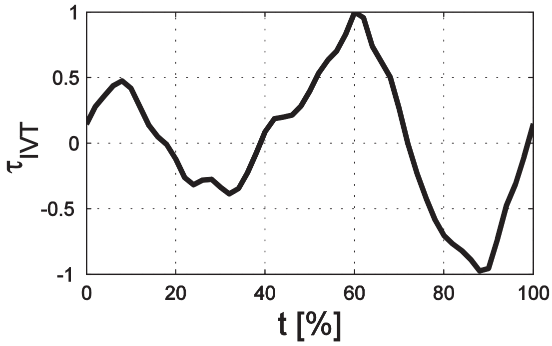

Fig. 5 Speed ratio of the IVT in level ground walking at the speed of 2.1 m/s

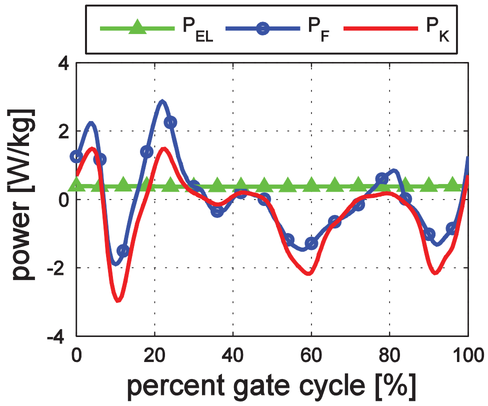

Fig. 6 Power requirements of the knee joint, the flywheel and the electric machine in the F-IVT. The assumed operating condition is level ground walking at 2.1 m/s. Power loss in all the components of the actuator is simulated in detail

TABLE II
ELECTRIC ENERGY AND PEAK POWER REQUIREMENTS IN LEVEL GROUND AT THE SPEEDS OF 1.1 m/s (a), 1.6 m/s (b), 2.1 m/s(c) AND 2.6 m/s (d) WITH F-IVT AND FR-D ACTUATORS

	Electric Energy Requirement [J/kg]		**Electric Peak Power [W/kg]**	
	F-IVT	**FR-D**	**F-IVT**	**FR-D**
a) 1.1 m/s	0,18	0,59	0,18	1,56
b) 1.6 m/s	0,27	0,81	0,22	1,95
c) 2.1 m/s	0,35	0,97	0,39	2,66
d) 2.6 m/s	0,30	1,00	0,33	3,65

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