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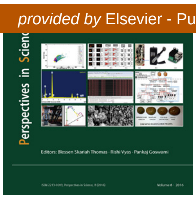

Mathematical modelling of a hand crank generator for powering lower-limb exoskeletons☆

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Summary With advances in technology and ageing societal concerns growing, personal care devices are gaining importance globally. One such area is lower-limb exoskeletons, used to assist persons to move around for normal daily living. Most of the commercially available assistive exoskeletons use rechargeable Li-ion batteries, which require frequent charging to meet the operational needs. Charging becomes a problem when a person relying on a mobility exoskeleton has to go outdoors for shopping or a leisure walk. Experimental data from on-going research to develop assistive mobility exoskeletons for elderly persons indicates that, the power required for exoskeletons is around 45—60 W which falls in the output range of hand-crank generators. So use of hand-crank generators as a charging source is discussed. In this work, we develop a mathematical model to investigate the potential of hand-crank devices in charging mobility exoskeletons and to give relation between input cranking speed and output charging power, and estimate the cranking time.

Introduction

Exoskeletons have been used for different purposes based on a variety of applications including human augmentation for military operations, rehabilitation in medical trauma cases and for assisting elderly persons for normal living tasks (Rupal et al., 2016). The power source for most of the exoskeletons developed is AC/DC power supply for charging the on-board Li-ion or Ni-MH batteries which drive the electrical motors (Bock et al., 2012). The weight of large batteries restricts their use in exoskeletons and hence small light batteries are often used which requires frequent charging.

This can be acceptable when the intention is to remain at or near the home where there is ample access to mains supply but the need for frequent charging becomes a problem, when travel outdoors for longer times is needed.

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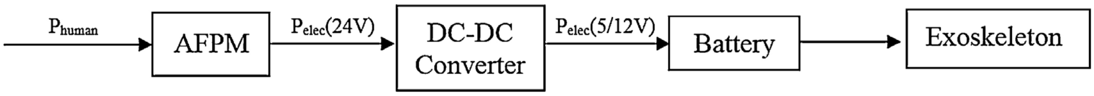

Figure 1 Open-loop block diagram of energy generation/supply process.

In this paper, we explore alternatives by exploring the energy needs for human motion and develop a mathematical model for charging exoskeleton's electrical batteries using human power. A flow chart of the power transfer process from the human motion needed to generate electrical power to charge electrical batteries which then are able to drive the electrical motors is presented. Power output of these devices varies from a few watts to 400 W in the case of merry-go-round generators (Dhand et al., 2016) and the use of such human powered approaches have been proposed to actuate low power exoskeletons in emergency situations (Dhand et al., 2016). A good example is the hand crank generator (HCG) where upper limb motion is used to turn a handle for generating electricity which can directly drive a motor or charge a battery with suitable devices. It has been observed that the power output using conventional HCGs is 50 ± 20 W depending on person to person. By using more efficient mechanisms, the power output can be increased to 60 W with high speed cranking and even to 100 W using three-phase HCGs (Ani et al., 2010; Moon et al., 2014).

Mathematical modelling

In order to assess the potential of human powering methods for assistive exoskeletons it is important to assess the energy requirements and how suitable amounts of power can be generated. For this, a mathematical model of the cranking process is needed and such a model is developed here starting with the torque generated at the crank and the current output produced to charge a battery. Due to losses, the total work transferred (W_t) to the generator shaft in N rotations of the crank is always less than the total work transferred by the human limbs (W_{t_H}) i.e. $W_t \leq W_{t\_H}$ (Yeo et al., 2015).

The applied torque (τ) is directly related to the output current (i_q) as described in (1).

$$\tau(t) = K_T \cdot i_q(t) \tag{1}$$

where K_T is the generator coefficient depending on the number of stator coils, number of magnetic pole pairs at the rotor, the air gap between stator and rotor, the type of the core material, the internal and outer radii of the rotor and other generator parameters.

According to Newton's second law,

$$J.\ddot{\theta}(t) = \sum \tau(t) \tag{2}$$

where J — polar moment of inertia; $\ddot{\theta}$ — angular acceleration; $\omega(t)$ — cranking speed and $\sum\tau = \tau(t)$ — net torque being applied on the system. Eq. (2) can be written as:

$$J\frac{d\omega(t)}{dt} = \tau(t) = K_T i_q(t) \tag{3}$$

Using Laplace transforms, relation of input cranking speed $\varpi(s)$ to output current $I_q(s)$ is:

$$\frac{I_q(s)}{\varpi(s)} = \frac{Js}{K_T} \tag{4}$$

Block diagram of the overall energy process

A block diagram representation of the energy generation process is shown in Fig. 1. The aim is to charge the battery (the output) with a given human effort (the input). The charged battery is then to be used to supply power to drive the actuator of an assistive exoskeleton. The human effort is the input mechanical power applied via a hand cranking device so that it feeds the generator (normally an axial flux permanent magnet (AFPM) generator) to provide electrical power as its output.

In most cases, the output from the generator is around 24 V DC, which can be modified according to the charging requirement of the battery by using a suitable DC—DC step down converter. Finally, the charged battery can be used to power the electrical motors to move the exoskeleton joints. Human power input is given as:

$$P_{\text{human}} = \tau \cdot \omega = \tau \cdot \frac{2\pi N}{60} \tag{5}$$

and the electrical power output from the AFPM generator is calculated as:

$$P_{\text{elec}} = V \times I \tag{6}$$

Clearly for a given hand crank generator with efficiency η,

$$P_{\text{elec}} = \eta \times P_{\text{human}} \tag{7}$$

where τ = input torque; V, I = output voltage and current from the generator respectively.

Estimation of the cranking time

The number of actuators in exoskeletons depends upon their degrees of freedom but sometimes mechanisms employing gear-trains, belts and pulleys are used to actuate two or more joints using a single actuator. Fig. 2(a) shows a lower-body exoskeleton developed in Gävle, Sweden to help elderly persons in performing mobility tasks such as sit-to-stand transfers and walking. A commercially available hand-crank generator is shown in Fig. 2(b), which can be used to charge the exoskeleton's battery. The output of the generators is in the range 24—33 V DC. However, in order to charge the exoskeleton battery 12/24 V DC is required. Therefore, a DC—DC step-down converter is used, as shown in Fig. 2(c). To perform a complete STS motion, the needed torque have to be produced at the hip, knee and ankle joints. Passive mechanisms can be used that involve actuating only one joint which is coupled to the other joints to complete

(a) (b) (c)

Figure 2 (a) Exo-Leg and actuator position (Gastriland, n.d.), (b) HCG (Aliexpress, n.d.), (c) DC—DC converter (Suntekstore, n.d.).

Table 1 Torque requirement at different joints during performing a STS posture.

STS time (s)	Maximum torque requirements for sit-to-stand (Nm)								
	Hip			Knee			Ankle		
	70 kg	80 kg	90 kg	70 kg	80 kg	90 kg	70 kg	80 kg	90 kg
1	91	104	117	80.3	92	103	56	65.3	72
2	57.3	65.3	73.7	70	80	90	33.3	38.3	43
4	49.7	56.8	63.9	67.2	76.8	86.4	28.7	32.8	36.9
7	45.3	52	58	66.3	76	85	25.6	29.3	33

one STS posture (Singh et al., 2016); we consider such actuation to simplify the energy requirements. For different STS times the maximum torques required at the hip, knee and ankle joints has been determined and is presented in Table 1.

Consider a healthy 90 kg person performing one STS motion in 1 s, 292 J of energy is required for actuating the exoskeleton via one joint. For 20 such STS transfers the amount of energy required is 5840 J. Assuming 100% losses at various stages, the total energy required for completing 20 STS postures is 11,680 J or 3.24 Wh. In this work, a 3.7 V 3.5 A h Li-ion battery is considered, that can store 12.95 Wh energy. There are many hand crank generators available that can give power outputs ranging from 10 to 65 W. The loss factor is found to be around 1.25 in field tests as the efficiency of these kinds of generators is around 80% (Wu et al., 2007). Time required to fully charge the battery = (12.95 W h/65 W) × 1.25 = 0.25 h, i.e. 15 min of cranking at the rated rpm can charge the 3500 mA h battery so that it is able to support 20 STS transfer motions. Similarly, the calculations can be reiterated for different HCG generators with different power outputs and also for different motions needed for normal daily living. The calculations give a rough idea about the cranking time needed to support the various motions.

Conclusions

In this paper, the idea of using human powered products is introduced using a simple mathematical approach to estimate the potential of the approach for charging assistive mobility exoskeletons. A mathematical model relating input human cranking torque/speed and output current has been developed and how this fits in the fuller energy generation/delivery approach which needs to be considered. It is shown that the approach is able to provide simple estimates of human cranking time for supporting simple human motions. From the discussions, it can be concluded that human motion effort offers a credible option to power mobility exoskeletons in emergency situations when battery life has run out.

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