Technical note

Cadence control system for paediatric functional electrical stimulation cycling

A. Pennycott*a, K.J. Huntb

a Ship Safety Research Centre, University of Strathclyde, United Kingdom
b Institute for Mechatronic Systems, Bern University of Applied Sciences, Switzerland

1. Introduction

The facility to exercise is important for people with a spinal cord injury (SCI). The injury often leads to a number of secondary health conditions in addition to the primary effects of paralysis and loss of sensation. For example, reductions in bone density following cessation of lower body exercise and loading due to injury can lead to increased risk of fractures, leading to comorbidities and reduced quality of life [1]. However, the severity of some of these complications can be reduced through effective exercise [2], and additionally, the physical capacities of SCI individuals are strongly influenced by exercise participation [3].

The child with SCI faces similar secondary conditions as adults, but additional problems such as joint contracture and hip instability are prevalent because the child is still developing [4]. Such factors can necessitate specialised adaptations to equipment for exercise in this group [5,6].

Functional electrical stimulation (FES) is a technique used to artificially induce muscular contractions in subjects where voluntary muscle activation is impaired, for example, due to a spinal cord injury. By harnessing these contractions in an appropriate sequence of muscle groups, it is possible to produce a torque capable of driving cycling motion [7].

FES cycling applied to adults with a spinal cord injury has demonstrated improvements in various areas. There have been reports of increases in endurance [8–12], muscle strength [9,13,14] and muscle volume [13,15,16], increases in power output [8,15,17,18] and peak oxygen uptake [8,15,17,19], increases in the bone mineral density (particularly of the distal femur) [1,14,16,18,20], increased range of joint motion [21], decreased vascular resistance [22,23] and physiological changes in exercised muscle [10,24]. There have also been reports of improved voluntary function following FES cycling training [13,16]. The magnitude of changes induced is strongly related to the intensity of training [8], while any improvements tend to be restricted to the exercised regions of the body [25], and are also followed by a detraining effect when training is stopped [18,20].

Preliminary results have demonstrated the feasibility of FES cycling amongst children with an SCI, using specially adapted trike equipment [5]. Results from paediatric FES cycling have shown improvements in bone mineral density, increases in muscle mass and strength and a lowered resting heart rate in participants [26]. However, these initial trials have also highlighted the fact that the cycling motion, unaided, can only be sustained for brief periods resulting from the relative weakness of this subject group [5]. The child with spinal cord injury, due to his or her smaller stature and lower muscle mass, has a more limited force generating capacity than an adult with SCI [6]. Moreover, the duration of cycling is limited not only by low power outputs but also by its inherently low efficiency, a trait shared by its adult FES cycling counterpart [27].
In addition to its applications in training, the utility of FES cycling as an exercise testing tool has been highlighted [28], where it can be used to determine key exercise indices. In order for such estimates (e.g. of steady-state oxygen uptake) to be reliable, it is necessary that both speed and cadence be controlled since the exercise ‘operating point’ depends on both of these variables [29]. Cadence is difficult to control through variations in braking torque since the increments of this resistance are normally a sizable fraction of a subject’s maximum power. This limited resolution also places restrictions on the range of cadences at which FES cycling may be performed which may be disadvantageous since it has been shown that higher forces are developed at lower cadences [30, 31], implying that low cadence training might be useful for strength training.

Finally, cycling outdoors would likely be a more enjoyable activity (as opposed to static indoor training) for subjects and therefore training and testing. The assistive torque would allow the exercise to be continued for longer durations thus providing a greater stimulus for cardiovascular improvement, and would also facilitate the exercise testing where a pre-set, constant level of angular velocity may be required. Following on from torque assistance developments in adult FES cycling [32], this paper examines the development of a feedback control system which regulates the cadence produced during paediatric FES cycling by varying the voltage delivered to an integrated electric motor.

2. Methods

2.1. Apparatus

The research employed a child’s trike (KMX Karts, UK), a magnetic braking device (Tacx, Netherlands), and a shaft encoder plus interface box (Hasomed GmbH, Germany). A 24 V, 200 W electric hub motor (Heinzmann GmbH, Germany) whose torque output can be varied via a potentiometer was also used in the tests. The various elements of the hardware can be seen in Fig. 1. The overall apparatus is similar to that employed in adult FES cycling [32]. Additional modifications of the trike are required [5] to accommodate the additional secondary complications of the child with spinal cord injury such as joint instability and spinal deformity [33].

2.2. Plant dynamics and system identification

The dynamic system relates the voltage applied to the motor with the resulting cadence (angular velocity) response. The overall system includes both the mechanical elements of the trike including inertia, gearing and friction and also the dynamics of the electric motor. When a cyclist is included in the set-up, there is the additional element of the mechanical linkage system of the subject’s legs and pedals as shown in Fig. 2. The torque produced by the subject via the electrical stimulation may be regarded as part of the disturbance $d(t)$ term.

Empirical models of the trike system were determined via a separate system identification test in which a cadence response was elicited using an input voltage to the motor of pseudorandom binary sequence (PRBS) form. From the input–output data, an ARX (autoregressive with exogenous input) model was determined for the system. The model structures are indexed according to the number of coefficients of $A$ and $B$—respectively $n_A$ and $n_B + 1$—and the value of the delay, $k$. Therefore, $arXABC$ is an ARX model with $(n_a, n_b + 1, k) = (A, B, C)$. Writing in terms of the backward-shift operator $q^{-1}$, the dynamic system model is

$$y(t) = \frac{q^{-k}B(q^{-1})}{A(q^{-1})} u(t) + \frac{1}{A(q^{-1})} d(t)$$

where the model polynomials are

$$A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-2} + \ldots + a_{n_A} q^{-n_A}$$

$$B(q^{-1}) = b_0 + b_1 q^{-1} + \ldots + b_{n_B} q^{-n_B}$$

and $u(t)$ and $y(t)$ are respectively the voltage input and the cadence output. Furthermore, the ARX model is also driven by the stochastic disturbance input $d(t)$.

The dataset from the identification test was divided into 2 roughly equal parts to give estimation and validation sets. Estimates of the plant polynomials $A$ and $B$ were obtained by least squares minimisation from the estimation set, while in order to compare the various models derived from the identification, the fit

![Fig. 1. FES cycling hardware consisting of orthoses, torque and cadence sensors, and a magnetic brake which varies the resistance.](image1)

![Fig. 2. Plant dynamics: the system includes the dynamics of both the motor, responsible for producing the torque $r$, and the mechanical system of the trike and the cyclist’s limbs. In the tests of this paper, the cyclist’s limbs are absent from the mechanics.](image2)
The fit criterion of Eq. (4) was applied to the validation set.

\[
\text{fit} = 100 \left[ 1 - \frac{1}{\text{N}} \sum_{i=1}^{\text{N}} \left( \frac{\hat{y}(t) - y(t)}{\hat{y}(t)} \right)^2 \right]^{0.5}
\]

Here, \( y(t) \) and \( \hat{y}(t) \) are respectively the measured and modelled cadence outputs at time \( t \) and \( \bar{y} \) is the mean of the measured output. The fit criterion thus uses the \( \text{N} \) sampled data points of the validation dataset to determine the percentage of the output variance accounted for by a given model.

2.3. Proposed feedback control system: structure, design and validation

The cadence controller adjusts the voltage delivered to the motor in real-time, so that the actual cadence follows the predefined reference cadence as shown in Fig. 3. In this scheme, a reference speed is specified within the software and the actual speed is then automatically controlled to this level, as opposed to being adjusted by a throttle. Speed adjustment via a throttle by a child could present some safety hazards.

The physical system of Fig. 3 was represented by the nominal, generic linear feedback structure of Fig. 4 in order to synthesise a closed-loop system of desirable properties. The control polynomials \( R(q^{-1}) \), \( S(q^{-1}) \) and \( T(q^{-1}) \) are the main elements to be calculated during control design and govern the control output signal \( u(t) \) as realised by Eq. (5). The application of feedback necessitates the measurement of the output \( y(t) \), introducing a noise term \( n(t) \) into the system to give the corrupted signal \( y'(t) \).

\[
u(t) = \frac{1}{R} \left( Tr(t) - Sy'(t) \right)
\]

With this configuration of plant and control polynomials, the overall closed-loop system governs the response of the output to the various system inputs is

\[
y(t) = \frac{q^{-k}BT}{AR + q^{-k}BS} \hat{r}(t) + \frac{R}{AR + q^{-k}BS} d(t) - \frac{q^{-k}BS}{AR + q^{-k}BS} n(t).
\]

Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>arx111</th>
<th>arx112</th>
<th>arx113</th>
<th>arx211</th>
<th>arx212</th>
<th>arx213</th>
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<td>Fit (%)</td>
<td>81.0</td>
<td>89.0</td>
<td>78.0</td>
<td>90.6</td>
<td>89.5</td>
<td>63.7</td>
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<tr>
<td>Model</td>
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<td>arx312</td>
<td>arx313</td>
<td>arx411</td>
<td>arx412</td>
<td>arx413</td>
</tr>
<tr>
<td>Fit (%)</td>
<td>91.0</td>
<td>89.5</td>
<td>70.8</td>
<td>91.5</td>
<td>89.3</td>
<td>70.1</td>
</tr>
</tbody>
</table>

The denominator common to each term of Eq. (6) was set to be the product of two polynomials, \( A_m \) and \( A_o \) which are respectively termed the control and observer polynomials, in order to obtain a closed-loop system with desirable properties [34]:

\[
AR + q^{-k}BS = A_oA_m
\]

The control polynomials \( R \) and \( S \) are computed through the solution of Eq. (7). Furthermore, in order to give a zero steady-state error to a given reference cadence, integral action was incorporated by including the polynomial \( (1-q^{-1}) \) as a factor of \( R \). \( T \) is set as the product of the observer polynomial \( A_o \) and a constant term \( \lambda \) so that the response of the output \( y(t) \) to the reference input \( r(t) \) was governed by the control polynomial \( A_m \), but not by the observer polynomial \( A_o \) due to forced cancellation [34]:

\[
T = \lambda A_o
\]

Given the above relationships, the transfer function relating \( r(t) \) and \( y(t) \) is \( q^{-k}\lambda B/A_m \). Setting \( \lambda = A_m(1)/B(1) \) gives a unity steady-state gain from input to output.

The properties of the overall closed-loop are set via those of the control and observer polynomials. The latter elements were assigned rise times and damping factors by calculating equivalent second order continuous time transfer functions from which the corresponding discrete time polynomials were numerically determined. The control polynomial which governs the response of the cadence output to a given reference input was allocated a rise time of 2 s, which was considered an appropriate rate of response, while the observer polynomial was assigned a rise time of 0.5 s. Both polynomials were given a damping factor of 0.99 and the sample time was set as 0.2 s.

In order to validate the closed-loop control system, reference cadences of various forms were applied to the physical system. These were of square-wave, sinusoidal and ramp format. The latter test allowed the system’s behaviour during saturation conditions to be demonstrated. Finally, the system’s response to disturbances was investigated in one test by (briefly) manually applying an arbitrary torque to the pedals. This test was performed to investigate the system’s stability and response when a fairly large disturbance was acting.

3. Results

3.1. System identification

The system identification tests yielded a series of empirical models with good levels of fit (Table 1). The identification results are shown in Fig. 5, plotting estimation and validation data separately and the latter set being accompanied by the output as simulated by identified model arx112 (defined in Eq. (9)). The model was able to predict the system’s cadence output with good accuracy. Measured data are plotted as solid lines and the cadence and voltage data displayed represent deviations from a steady-state operating point rather than being absolute values of the variables.
In general, increasing the order of the model increased the fit values, as shown in Table 1. As a compromise between the fit achieved and model order, the arx112 model given in Eq. (9) was selected for control design. This model has a rise time of approximately 2 s.

\[ y(t) = \frac{213.4q^{-2}}{1 - 0.7456q^{-1}} u(t) + \frac{1}{1 - 0.7456q^{-1}} d(t) \]  

\[ A_m(q^{-1}) = 1 - 1.4526q^{-1} + 0.5276q^{-2} \]  

\[ A_o(q^{-1}) = 1 - 0.5559q^{-1} + 0.0775q^{-2}. \]  

Using model (9) and the polynomials above, the control polynomials were calculated to be

\[ R(q^{-1}) = 1 - 1.2629q^{-1} + 0.3178q^{-2} - 0.0548q^{-3} \]  

\[ S(q^{-1}) = (0.7181 - 0.5347q^{-1}) \times 10^{-3} \]  

\[ T(q^{-1}) = (0.3515 - 0.1954q^{-2} + 0.0272q^{-2}) \times 10^{-3} \]

while the vector margin was 1.0.

3.3. Feedback control tests

The feedback controller was able to provide accurate tracking of square-wave (Fig. 6(a)), sinusoidal (Fig. 6(b)) and ramp (Fig. 6(c)) reference signals. Satisfactory disturbance rejection performance was also achieved (Fig. 6(d)). In addition to achieving cadences close to the reference signals, the system showed satisfactory behaviour during saturation conditions in the test utilising a ramp input as the reference cadence, with no wind-up behaviour being observed (Fig. 6(c)).

4. Discussion

The aim was to develop a closed-loop control system which would automatically regulate the angular velocity produced at the crank during paediatric functional electrical stimulation cycling. The proposed control approach was demonstrated to be feasible and produced a cadence output that closely followed the reference signal, and furthermore demonstrated acceptable behaviour during saturation and disturbance scenarios.

The control system has practical applications in exercise testing and in training, including recreational, outdoors cycling. In the case of exercise testing, it is important to closely regulate certain variables, including cadence. The motor allows training for longer durations which would otherwise be unfeasible due to weakness and rapid fatigue development seen during FES stimulation of the child with SCI. The torque assistance provided by the motor enables the user to overcome gradients, inertia and wind resistance, and as such, may be the only practical means to realise recreational, outdoors FES cycling for the child with spinal cord injury.

The cadence control system presented here shares many features of those systems found in adult FES cycling [32]. However, additional modifications and safety provisions are required in any system used by the child with SCI due to the higher fragility of this population. Hardware modifications of the trike itself and orthoses are needed, and extra care taken regarding how to set and control cadence and stimulation inputs must be taken. In the event of a hazard, for instance due to injury, emergency stop mechanisms must be in place and be rapidly accessible. The cadence control concept has now been successfully employed in paediatric FES cycling studies [6].

Greater levels of fit were achieved using higher orders of model in some cases e.g. arx411. However, the magnitudes of these increases were small and therefore, the lower order model with good fit (arx112) was selected since it is normally considered desirable to synthesise a control system of low order.
The vector margin of 1.0 indicates that the control system has good robustness of stability. This is important because even though the model demonstrated a good fit to the experimental data, the physical system was identified in the absence of a cyclist in the apparatus. The addition of a subject changes the physical properties of the system—principally the inertia—and the subject’s torque contributions (produced artificially through stimulation) will also play the role of a disturbance. Therefore, the underlying dynamics will change with the inclusion of a subject and a large vector margin is necessary in order to prevent instability resulting from the consequent deviation from the nominal model. Nevertheless, preliminary results from actual FES cycling using the controller developed in this paper at Shriners Hospital for Children demonstrate that the system has a stable response when a subject is included in the dynamics [6,33].

The cadence controller presented here may be combined with an additional power controller whose objective is to regulate the work rate produced by a subject through online variation of the stimulation intensity. An approach to combining the two control loops is presented by Hunt et al. [29]. The dynamics underlying power generation via stimulation are subject to a high degree of uncertainty since the system is very sensitive to several factors such as electrode positioning and the physical condition of a subject, both of which can vary between tests. Moreover, the system can change in the course of a single test as a result of fatigue. Consequently, the system underlying the cadence control system, although dif-
ferent across subjects, has a lower uncertainty and for this reason is normally set to have a faster response than the power control loop and thus assigned a higher closed-loop bandwidth when the two systems are to run in parallel.

5. Conclusions

The proposed closed-loop system provides an effective means of eliciting a desired cadence response from the FES cycling system. The system can now be utilised in further exercise testing and training using paediatric FES cycling where a fixed level of cadence is required, perhaps in combination with a power controller.

References