XVII International Symposium on Computer Simulation in Biomechanics
July 28th – 30th 2019, Alberta, Canada

FINDING THE PERIODIC MUSCLE FIBER LENGTH OVER TIME THAT MAXIMIZES AVERAGE MECHANICAL POWER OUTPUT DURING SPRINTING

Edwin D.H.M. Reuvers, Dinant A. Kistemaker and A.J. "Knoek" van Soest
Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
Email: dinant.kistemaker@gmail.com

INTRODUCTION

The average mechanical power output (*AMPO*) is a performance determining factor in many sports disciplines. Sports equipment for periodic movements like sprint cycling should therefore be designed to allow muscles to deliver maximal *AMPO*. The design of such equipment would greatly benefit from knowledge of the determinants of *AMPO* at the level of a single muscle. Surprisingly however, the relation between muscle length/stimulation over time and resulting *AMPO* has not been studied extensively. A rare study examining this issue experimentally *in vitro* was done by Askew and Marsh [1], who investigated how cycle frequency and fraction of cycle time spent shortening (*FTS*) affected *AMPO* in mouse muscle. Although insightful, a limited set of muscle length/ stimulation histories was investigated in that study and it is thus unclear if the muscle length/ stimulation over time was identified that maximizes *AMPO*.

In this modeling study, we used a Hill-type muscle model to determine, for a short-duration sprinting task, the periodic contractile element (*CE*) length and stimulation over time that resulted in maximal *AMPO*.

METHODS

The behavior of *CE* was modeled using a Hill-type muscle model in which *CE* force depends on active state, *CE* length (l_{CE}) and *CE* velocity [2]. Activation dynamics was modeled according to [3] using parameter values for fast twitch (*FT*) muscle. The isometric active force-length relationship was modelled as a second-order polynomial with a maximum (F_{max_isom}) at optimum l_{CE} (l_{CE_opt}) and two zero-crossings at (1±0.56)•l_{CE_opt}. The concentric force-velocity relation was modeled using Hill's equation with a maximal contraction velocity (v_{max}) of -12.7 l_{CE_opt} s^{-1}. The eccentric force-velocity relation was modeled as described in [4]. The muscle model was formulated such that all functions had continuous first derivatives and were useable for Direct Collocation (see [5]).

The optimization problem was to find the periodic l_{CE} and muscle stimulation over time that maximized *AMPO* at imposed cycle frequencies ranging from 0.2 to 5.0 Hz. This optimal control problem was transformed into a parameter optimization problem using a Direct Collocation method and was solved using SNOPT.

All results were normalized for the product of l_{CE_opt} and F_{MAX_isom}, allowing the results to be readily scaled to any particular muscle. For example, a human *m. quadriceps* with a l_{CE_opt} of ~0.09 m and a F_{MAX_isom} of ~7000 N yields a scaling factor of ~630 N•m.

RESULTS AND DISCUSSION

The mechanical work per cycle decreased as cycle frequency increased (Fig. 1) and is due to the effects of activation dynamics and the force-velocity relationship. The product of mechanical work per cycle and cycle frequency (i.e. *AMPO*) peaked at ~0.57 s^{-1} at 2.0 Hz. In passing we note that this cycle frequency is similar to the optimal cadence in human sprint cycling [2,6].

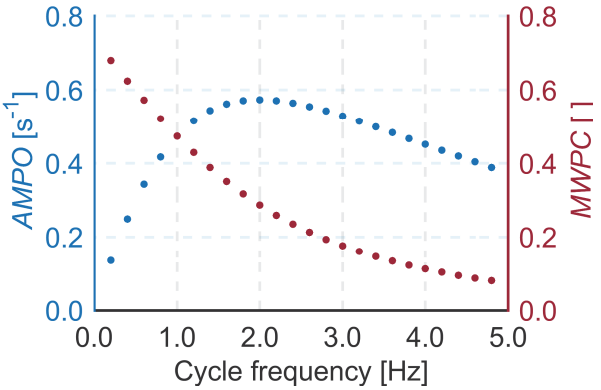

Fig 1: Average mechanical power (*AMPO*) and mechanical work per cycle (*MWPC*) as a function of cycle frequency.

As expected, the average l_{CE} was close to l_{CE_opt} for all cycle frequencies and the optimal muscle stimulation was found to be either fully on or off (Fig. 2). The identified optimal l_{CE} amplitude (a trade-off between the concentric force-velocity relationship on one hand and the force-length and the eccentric force-velocity relationships and activation dynamics on the other) was ~0.36•l_{CE_opt} at optimal cycle frequency and decreased with cycle frequency. Optimal *FTS* (a trade-off between the force-velocity relationship on one hand and activation dynamics and shortening time on the other) was

~0.76 at all cycle frequencies, which is in agreement with [1]. The transition from lengthening to shortening was sharper than that from shortening to lengthening, which is caused by a much faster activation than deactivation in the model used [3].

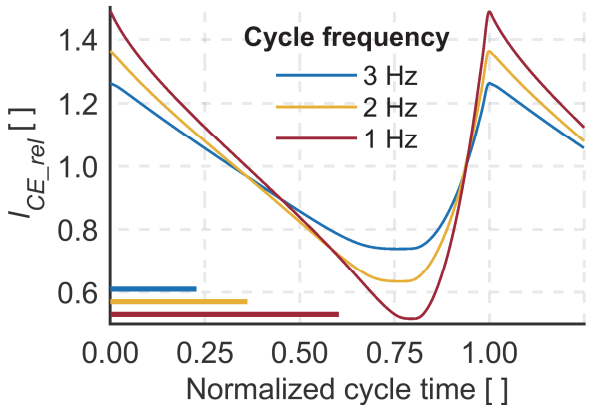

Fig 2: Relative CE length ($l_{CE\_rel} = l_{CE} / l_{CE\_opt}$) as a function of normalized cycle time. Optimal muscle stimulation was fully on during the (normalized) time indicated by colored bars and was off elsewhere.

The sensitivity of *AMPO* for cycle frequency and *FTS* is shown in Figure 3. The influence of cycle frequency and *FTS* on *AMPO* are independent of each other. From Figure 3 it can also be observed that, near the optimum, *AMPO* is quite insensitive for changes in cycle frequency and *FTS*. For example, at the optimum cycle frequency of 2.0 Hz, *AMPO* was within 95% of its maximum for *FTS* ranging from 0.55-0.92. Similarly, at 0.76 *FTS*, *AMPO* was within 95% of its maximum value for cycle frequencies ranging from 1.7-2.5 Hz.

The dependence of results on muscle fiber type was investigated by changing v_{max} from the used *FT* value of -12.7 l_{CE_opt} s^{-1} to -4.2 l_{CE_opt} s^{-1} (which is more typical for slow twitch (*ST*) muscle), and using activation dynamics parameter value for *ST* muscle [3]. It was found that, compared to *FT* muscle, both the optimum cycle frequency and *AMPO* for *ST* muscle decreased with a factor of ~3, which is similar to the ratio of *FT* and *ST* parameter values. In contrast, optimum *FTS* was insensitive for muscle fiber type.

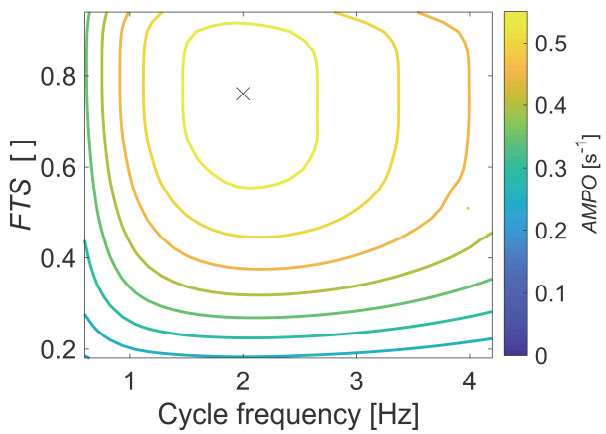

Fig 3: *AMPO* as a function of cycle frequency and *FTS*.

In future work, we intend to use the results of this study as a starting point for validation studies and, subsequently, for the design of mechanisms that maximize *AMPO*. In addition, we intend to investigate the optimal muscle length and stimulation for criteria other than maximal *AMPO*.

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