Muscle-Driven Solutions for Rehabilitation and Control

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Innovative technologies in muscle rehabilitation are increasingly explored to promote motor recovery and enhance patient interaction with assistive devices. This doctoral dissertation presents four novel contributions in this domain, focusing on Functional Electrical Stimulation (FES) control, Human-Machine interfaces (HMIs), event-based data acquisition sensors, and muscle activity estimation using musculoskeletal models. Central to all these developments is muscle activity, and consequently the surface ElectroMyoGraphic (sEMG) signal. Built on top of it, and leveraged in most of these applications, is the Average Threshold Crossing (ATC) technique.

The first contribution is an optimized FES control system based on the ATC technique for real-time modulation of biomimetic stimulation profiles. An in-vivo experimental campaign was conducted on 17 healthy subjects performing 6 different movements, resulting in a median cross-correlation coefficient of 0.91 between the reference and the FES-induced motion, with a median replication delay of 800 ms, and processing latencies of 7 ms when a Raspberry Pi is used as control platform. Moreover, a novel algorithm for FES calibration enabling the synergistic control of multiple channels was introduced and tested on 8 healthy subjects, also resulting in a slight increase of movement replication performance.

The second contribution is a custom armband for hand gesture recognition, also taking advantage of the ATC approach for minimized power consumption. Targeting 8 active gestures plus the idle state, after a training phase involving 20 healthy subjects, the on-board classifier of the armband succeeded to reach a 91.93 % average accuracy in a first testing campaign. A calibration algorithm was later introduced to handle the angular displacement and reverse wearing of the armband, and a testing campaign on 25 healthy subjects who arbitrarily wore the device resulted in an average classification accuracy of 93.36 %, along with a processing latency of 1.75 ms and a mean current absorption of 2.9 mA.

The third contribution is an upgrade of the ATC technique, allowing its use without the need for a threshold calibration phase, thus facilitating its integration

into sEMG acquisition sensors. Among the obtained results, besides a current consumption of only 12.92 µA, a median increase in the number of events of more than 25 % was achieved by varying the exerted muscle force in steps of 20 % MVC.

The fourth contribution introduces an algorithm for estimating the muscle activations required to achieve a target movement, leveraging recently developed musculoskeletal models. Evaluated in both upper and lower limb simulations, the algorithm generates smooth muscle activation patterns that enable kinematic replication RMSEs lower than 4° for slower movements up to 11.7° for the fastest motions tested. The algorithm is able to perform hundreds of simulation iterations per second and thus can be used close to real-time, paving the way for its integration into existing applications where musculoskeletal dynamics can drive the results toward more physiological outcomes.