Bi-articular muscles as optimum force providers

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Introduction

Bi-articular muscles, when interpreted as actuators of living organisms, are difficult to understand from a technical point-of-view. The fact that bi-articular muscles affect two joints simultaneously with a predefined ratio between the exerted moments appears to limit their applicability in organisms that must be versatile enough to withstand a wide range of external loads. Also from a control point-of-view, bi-articular muscles appear to complicate the task much beyond what is necessary. This has caused several authors to speculate on the role of bi-articular muscles as moment transferors between joints [1] and force direction controllers [2].

Due to the predefined ratio of exerted joint moments, bi-articular muscles always work in collaboration with mono-articular muscles. The complexity of even the simplest practical cases is therefore large enough to make physical interpretation of the function of each muscle in the system very difficult and perhaps even irrelevant. It may in fact be true that the muscles work as an integrated system and cannot be understood individually. An alternative is to interpret a given muscle configuration as one of many possible mass or strength distributions between actuators. We may then investigate to which extent the given configuration is optimal and attempt to understand the bi-articular muscles in this context. In other words, are the bi-articular muscles justified as optimum force providers?

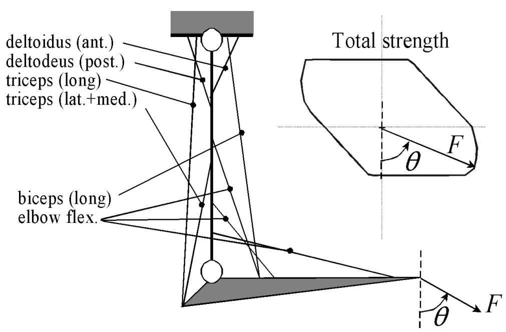

Fig. 1: Elbow and shoulder model according to [3].

Methods

We shall use a two-dimensional numerical model of an arm equipped with 8 muscles and loaded by a force with variable direction as shown in Fig. 1. Notice that both joints are spanned by anterior as well as and posterior mono-articular muscles, and it is consequently possible to balance any load without the use of bi-articular muscles.

The software is organized into an analysis part wrapped in a general optimization algorithm. The analysis part contains a min/max solver that determines the force in each muscle as a function of the external force direction as described in detail in [3]. The polar graph in Fig. 1 shows the initial muscle configuration's strength against forces of different angles. The optimizer can identify model parameters that cause a desired behavior of the model. We attempt two optimizations. In the first run, we minimize the sum of muscle strengths in each direction of the external force, maintaining the total strength in each direction depicted in Fig. 1. The definition of the second optimization problem is similar except that we now require that no muscle be overloaded at any exterior force angle, i.e., we find a muscle configuration that is optimal for carrying all loads.

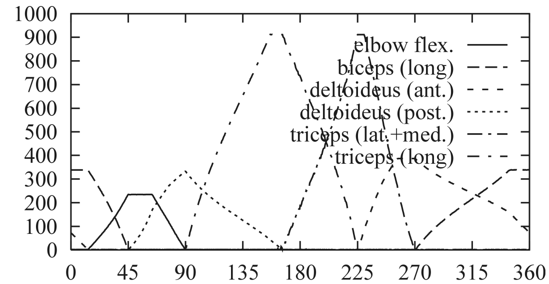

Fig. 2: Optimized strength [N] for each angle, θ [deg.].

Results

The result of the first optimization is illustrated in Fig. 2. Notice that the optimization leaves no more than two muscles in the model at any exterior load direction. This is consistent with optimum design theory which states that single load case designs are statically determinate, i.e., we need not have more muscles than we have degrees of freedom. However, we also notice that the bi-articular muscles are present over 270 degrees of the 360 degrees load spectrum. This indicates that the bi-articular muscles do indeed play a positive role in balancing the exterior load.

The second optimization problem turns out to have multiple optima of the same objective function value. They all reduce the sum of muscle strengths by 23%. The sum of bi-articular muscles is either maintained or increased slightly, whereas the mono-articular muscles are reduced in all cases.

Discussion and conclusions

The definition of the optimization problem used in this work is most probably not identical to the criterion that drives the development of human muscles. In spite of this, the model provides an argument for the assumption that bi-articular muscles play an important role in carrying external loads and providing versatility for different loading situations, even in static cases. Balancing the same load with only mono-articular muscles requires a larger total cross-sectional area.

Similar work on more realistic models including more muscles, motion, tendon elasticity, and force-length-velocity dependency of muscle strength is in progress.

References

[1] R.L. Lieber (1990) Hypothesis: biarticular muscles transfer moments between joints. Developmental Medicine and Child Neurology 32, 456-458. [2] B.M. van Bolhuis, C.C.A.M. Gielen, G.J. van Ingen Schenau (1998) Activation patterns of mono- and bi-articular arm muscles as a function of force and movement direction of the wrist in humans. J. Phyisology, 508, 313-324. [3] J. Rasmussen, M. Damsgaard, M. Voigt (2000) Muscle recruitment by the min/max criterion, part 2: implementation and application. Submitted for publication.

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