Parameter Investigation of Muscle-like Actuators

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Abstract— **This paper investigates the influences of different muscle parameters on the behavior of a simulated dynamic arm system, when using a Hill-type muscle model. The effect of different muscle parameters on both obtainable angles and stiffnesses of the arm are evaluated. Aside from the investigations of the muscle parameters, the potential for controlling such a muscle actuated system using a simple linear controller is evaluated. The simple control approach is tested on both a simple one degree-of-freedom system with two muscles as well as a two degree-of-freedom system with four muscles. The results of the parameter investigation yield a much clearer picture on how the different parameters affect the performance of the muscle actuated system. Experiments show that simple linear controllers yield surprisingly good control performance for the non-linear muscle actuated systems. Thus, this study gives insights on how to setup an effective muscle system, how to tune the muscle and control parameters of such as system, as well as which parameters biological systems may be controlling to achieve computationally inexpensive but still highly effective body control.**

Keywords: muscle model, parameter evaluation, dynamic arm control, linear muscle control, performance

I. INTRODUCTION

In the recent years, the desire to utilize muscle-like actuators for control of robotic systems has gained a considerable amount of attention. A short review of previous work on muscle models is presented in [1], along with a discussion of the different available muscle models. The key reasons for using muscle-like actuators include a desire to mimic human movement, taking advantage of the inherent self-stabilization of muscle actuated system, as well as the fact that muscles provide more flexibility to a given system. The flexibility of muscle-like actuators has for instance been explored for grasping purposes in [2] using a 20-DOF Shadow Hand [3] based on pneumatic muscles. For the purpose of mimicking human movements, simulation studies such as [4] and [5] include muscle models for obtaining movements that are comparable to human performance of a given task. Also, a considerable amount of work has been done with respect to artificial muscles using, e.g., pneumatics [6], [7], [8], [1], [9].

The purpose of this paper is to investigate how the different parameters of a muscle will affect the performance of a given system. To do this, a muscle model is presented in section II-A along with the various parameters to be tested. The model is then used in an artificial arm simulation to investigate how the system reacts to particular parameter changes. A key aspect in this investigation is that contrary to [10] and other similar approaches, we do not attach the muscles at fixed angles relative to the limbs of the system. When the angle of a joint changes, the relative angle between the muscle/tendon and the limb it is attached to will change as well. Thus, the relationship between the angle, as well as the stiffness of a joint, relative to the activation level of a given muscle will change in a non-linear manner.

In the next section, a description of the used muscle-type is given, followed by descriptions of the simple muscle-based arm simulations used for the tests. Then the effect of the different muscle parameters on consequent joint angles and stiffnesses is investigated in Section III. Next, experiments are reported where the muscles are controlled by a simple linear controller. Finally, the paper is concluded in Section V.

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II. SYSTEM DESCRIPTION

The primary focus of this paper is to investigate how the choice of parameters in an artificial muscle model can affect the performance of the system. To do so, it is first necessary to describe the muscle model used. Following that, two different simulated systems, which are the targets of the investigation, are presented.

A. Muscle Description

The muscles that are used in this work are based on the Hill-type muscle model [11], [1], which has been widely used [12] and whose basic structure is shown in Fig. 1.

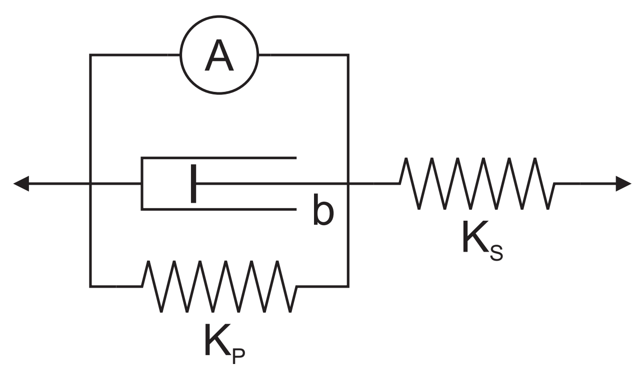

Fig. 1. Equivalent model of a muscle using spring/damper components.

Such a muscle consists of two spring elements, one placed in serial, K_s, and one placed in parallel, K_p, one damping element, b, and one contraction element, A. The contraction element is the neurally controlled element, that contracts when subjected to a signal from an attached signal source. This corresponds to the element that is directly controlled by the α-motor neuron in biological muscles. The damping element is a limiter, which ensures that fast changes to the muscle length reduce the tension the muscle is capable of producing proportionally. Finally, the springs mimic the spring-like properties of real muscles. The differential equation describing the movement of the Hill-type muscle is given by

$$\dot{T}(t) = \frac{K_S}{b}\left(K_P x(t) + b\dot{x}(t) + A(t) - \frac{K_S + K_P}{K_S}T(t)\right) , \quad (1)$$

where $T(t)$ is the tension in the muscle, $x(t)$ is the length of the muscle, and $A(t)$ is the activation level of the α-neuron at time t.

B. Simulated Arm Descriptions

For the various tests in this paper, two basic arm systems are investigated. These are a 1 degree-of-freedom (DOF) arm controlled by two muscles and a 2 DOF arm controlled by four muscles. Before describing the actual systems, some commonalities to all simulations performed in this paper are given.

1) Common Simulation Conditions: The arm is initialized with all joints set to an angle of $0rad$. The muscles are initially set to an activation level of 0 and when the simulation starts, the activation level of each muscle is set to the desired value, which remains constant throughout the simulation. Thus, no active control strategy is used. The internal dynamics of the muscles are the only influence on the movement of the arm during the simulation. The simulation is run until all muscles come to rest. A muscle is considered as being at rest when the tension of the muscle changes less than $10^{-11}N$ and each of the muscle spindles change less than 10^{-12} between subsequent samples. Further information about muscle spindles can be found in [13], [14], [15]. After all muscles have been detected as being at rest, the joint angles and the stiffnesses are considered to have also sufficiently converged.

The above principle of moving the system based on fixed activation levels of the muscles roughly corresponds to control of the system using equilibrium point trajectories as postulated in [16], [17]. Whether or not this applies to how movement is actually performed in natural systems is discussed in [18]. For the basic parameter investigations in this paper, the method is considered appropriate.

2) 1DOF Arm: The 1DOF arm used for the simulations is sketched in Fig. 2. It consists of a 0.4m hinged limb with an antagonistic muscle pair attached symmetrically to it. The muscles are attached to the limb in a distance of 0.3m from the hinged end of the limb, and on the other end they are kept fixed to the environment. This allows the limb to move freely within an angular range of $[-\frac{\pi}{2}; \frac{\pi}{2}]$. Depending on the muscle parameters and activation levels, the actual movement of the arm will occur in a smaller range due to the limitation of the muscle-configuration.

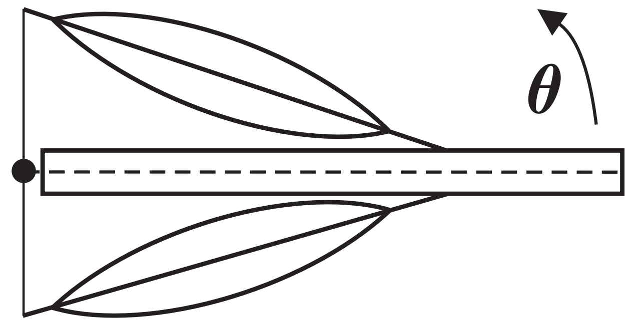

Fig. 2. Sketch of the 1DOF system.

3) 2DOF Arm: The used 2DOF arm, which is sketched in Fig. 3, is an extension of the 1DOF arm. The extension consists of an added limb of 0.4m that is hinged to the end of the base limb used in the 1DOF arm. An antagonistic muscle pair is attached across the hinged joint to each limb at a distance of 0.3m from the hinge. Further, an attachment point for each muscle is added at a distance of 0.1m from the hinge in a direction perpendicular to the base limb. This configuration provides the muscle with a better angle of actuation on the outer limb and thus allows for a more responsive actuation. For the sake of simplicity, the 6-muscled actuation of 2DOF arms normally used, e.g. in [10], [19], [5], is not considered. Not only would the number of muscles have to be increased from 4 to 6, thus resulting in an increase of the dimension of the input space, but the increased interaction between the muscles would also have complicated the analysis of the obtained results.

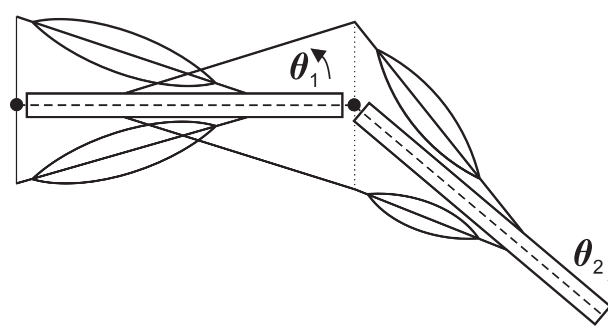

Fig. 3. Sketch of the 2DOF system.

III. PARAMETER INVESTIGATION

The following investigation of the effect of the parameters on the obtainable angles and stiffnesses of a given system is mainly performed on the simple 1DOF system. However, the experiments performed on the 2DOF system in Section III-E are also included in order to investigate how the muscle system is capable of handling cross-couplings between different limbs.

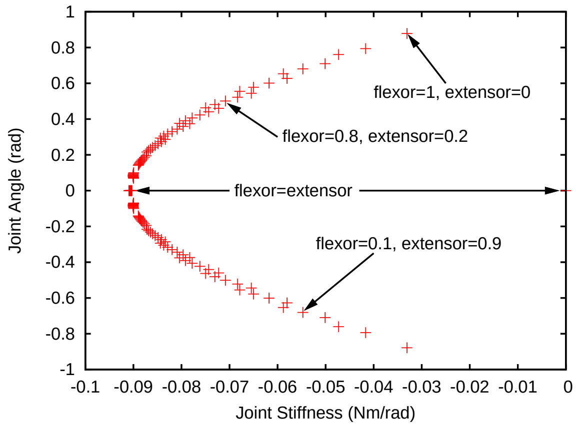

Fig. 4. Relationship between joint angle and stiffness for 1DOF muscle controlled arm with balanced muscles.

A. Joint Stiffness

Due to the way the muscles are attached to the limb, the stiffness of the joint is not proportional to the forces produced by the muscles. As the angle of the muscle relative to the limb changes, the contribution of each muscle to the stiffness of the joint changes non-linearly. Generally, the stiffness of a joint i can be found according to

$$k_i = \frac{\partial \tau_i}{\partial \theta_i} \quad , \tag{2}$$

where τ_i is the torque affecting joint i and θ_i is the angle of the joint around a given rotational axis.

The relationship between the obtainable angles of the joint and the corresponding stiffnesses for a set of balanced muscles are show in Fig. 4, obtained using a set of 11x11 equally spaced activation levels of the two muscles.

The balanced muscles have identical muscle parameters[1]. The rest lengths are balanced such that they correspond to the exact length of each muscle for a joint angle of $0 rad$. The figure shows that when neither muscle is activated, an angle and stiffness of 0 is obtained, whereas for any activation of the muscles, a characteristic tradeoff between angle and stiffness is evident. By closer examination, it can also be seen that for a given angle, a small range of possible stiffnesses are obtainable and vice versa. However, as the ranges are quite small, the flexibility with regard to obtaining different stiffnesses for a given angle for this particular system is limited.

B. Effect of Muscle Rest Length

To test the effect of the rest length of the muscles on the attainable angles and stiffnesses of the controlled joint, some additional simulations were run using the same settings as previously, except for the muscles' rest lengths. The muscles' rest lengths were tested using the values 0.2m (short) and 0.4m (long), respectively. The results of running those simulations are shown in Fig. 5.

[1]The spring and damper coefficients are inspired by values found for a femur muscle in a cat [15]: $K_{1e_p} = K_{1f_p} = 7.5$, $K_{1e_s} = K_{1f_s} = 13.6$, $b_{1e} = b_{1f} = 5$, and $x_{1e_{rest}} = x_{1f_{rest}} = 0.316$

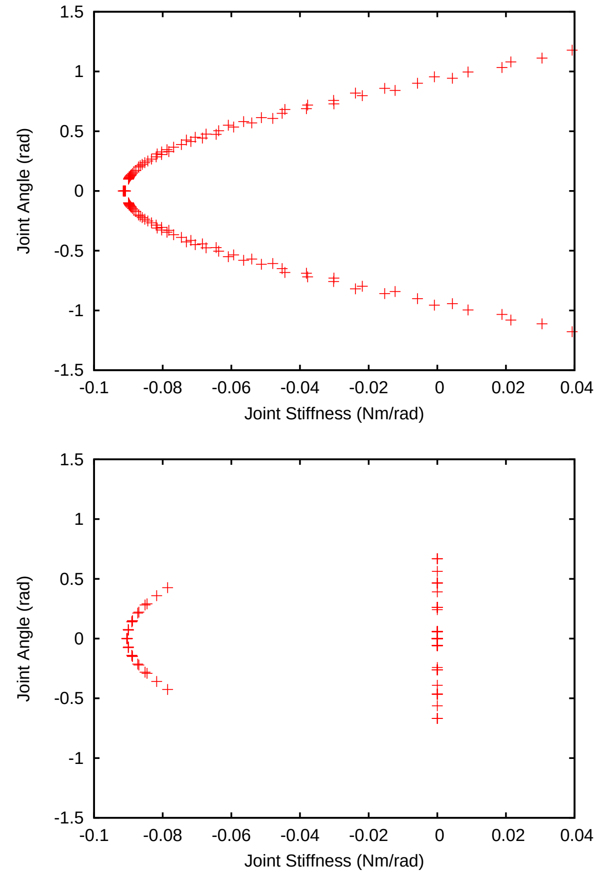

Fig. 5. Relationship between joint angle and stiffness for 1DOF muscle controlled arm with short (top) and long muscles (bottom).

For the short muscles, the range of obtainable angles were increased slightly. However, for the most extreme angles, the stiffness of the joint turns out to be positive, indicating that those angles are unstable equilibrium points for the joint. This means that any external disturbance acting on the joint in these unstable equilibrium points will not be countered by the system, but will in fact be amplified by the system, thus driving the system even further from the given equilibrium point. The reason why the system can settle in such unstable equilibrium points at all, is due to the way the experiments are performed using constant excitation values throughout the simulation combined with the presence of friction in the simulated system. The short muscles also cause a greater amount of effort to be used, as the muscles are always contracting considerably, at least when compared to the balanced case. Correspondingly, when the rest length is increased, the range of obtainable angles decreases. As the figure also shows, a lot of different joint angles can be obtained with a corresponding stiffness of 0 for these long rest lengths. So, despite the muscles having a low non-zero level of neuronal activation, an increased rest length simply results in both muscles being at rest for a large range of different joint angles. For these cases, the long muscles are however very efficient as they do not need to maintain a tension level in order to maintain the position, provided that

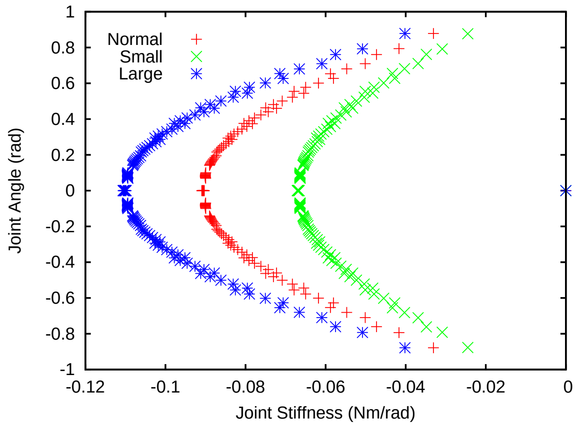

Fig. 6. Relationship between joint angle and stiffness for 1DOF muscle controlled arm with different K_s parameters ($K_{S_{small}} = 6.8$, $K_{S_{large}} = 27.2$).

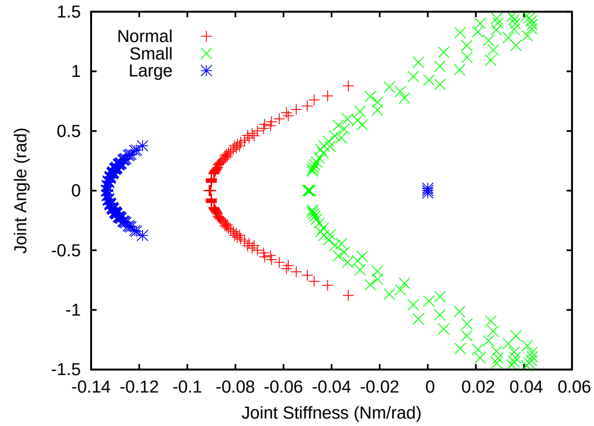

Fig. 7. Relationship between joint angle and stiffness for 1DOF muscle controlled arm with different K_p parameters ($K_{P_{small}} = 3.25$, $K_{P_{large}} = 15$).

no disturbances affect the system.

C. Effect of Serial Spring Element

In this section the effect of varying the serial spring element K_S is investigated. The variations correspond to a doubling and a halving of the parameter when compared to the baseline tests in Sec. III-A, while all other settings are kept identical to the previously used values. The obtained results are shown in Fig. 6.

Changing the parameter clearly does not affect the range of obtainable angles of the system. Indeed, the distribution of the angles when related to the muscle activation levels appears to remain the same as well. However, a clear change is seen with respect to the stiffness of the joint. A decrease in K_S values causes the obtainable stiffnesses to be numerically significantly lower, and the joint in this case will be more susceptible to external disturbances. Correspondingly, when the parameter is increased, the stiffness of the joint becomes numerically higher, and such a system will thus be better suited to counteract any external disturbances.

D. Effect of Parallel Spring Element

Running the simulations using different values for the parallel spring element K_P results in the angle/stiffness trade-offs shown in Fig. 7.

From the figure it can be seen that changing K_P has different effects on the obtainable angles and stiffnesses of the system. When the parameter is increased, the stiffness also increases, and vice versa. Additionally, an increase in K_P also causes the obtainable range of angles to decrease considerably. However, even though a decrease of K_P results in a larger range of obtainable angles, it is also worth noting, that the extreme angles result in unstable equilibrium points with positive stiffness values. A further property of the increased rest length is that the range of stiffnesses possible for different angles increases as the joint angle increases. Thus, even though the general stiffness decreases with a decrease in the parameter, the available range of stiffnesses is increased.

E. 2DOF Arm

The relationship between the angles and stiffnesses of the joints of the 2DOF arm for joint-wise balanced muscles are shown in Figure 8 using a set of 5x5x5x5 evenly distributed activation levels of the four muscles involved.

The balanced muscles for the base joint have the same values as those for the balanced 1DOF shown in Fig. 4, whereas the muscles for the outer joint have a longer muscle rest length[2]. It is obvious from the figures that using the same parameters and balanced rest lengths result in joints with similar characteristic shapes in the same ranges. In fact, the results for the outer joint are more or less identical to those obtained for the 1DOF system. The reason why the base joint graph contains a wider range of points compared to the range for the outer joint is due to the cross coupling with the outer joint. Depending on the activations of the muscles for the outer joint, and thus also the forces acting around the outer joint, the angle and stiffness of the base joint are affected. The effect arises solely due to the additional forces around the outer joint acting as disturbances on the inner limb, thus shifting the equilibrium points of the base joint slightly depending on the size of the disturbance.

An interesting aspect to notice in Fig. 8(a) is the small number of activations that create an angle around $0 rad$ and stiffnesses between -0.05 and $-0.04 Nm/rad$. This occurs due to the non-symmetry of the muscles, which can actively contract, but not push. As such, when one muscle does not exert any tension, it also does not contribute to the joint stiffness, and only the contribution from the other muscle will provide stiffness for the joint. When this is combined with the effect of the cross coupling from the outer joint, the result are regions in which the inner joint uses only one muscle to counteract the cross coupling effect from the outer joint.

Based on the above findings, it can be concluded that when

[2] $K_{2e_p} = K_{2f_p} = 7.5$, $K_{2e_s} = K_{2f_s} = 13.6$, $b_{2e} = b_{2f} = 5$, and $x_{2e_{rest}} = x_{2f_{rest}} = 0.632$

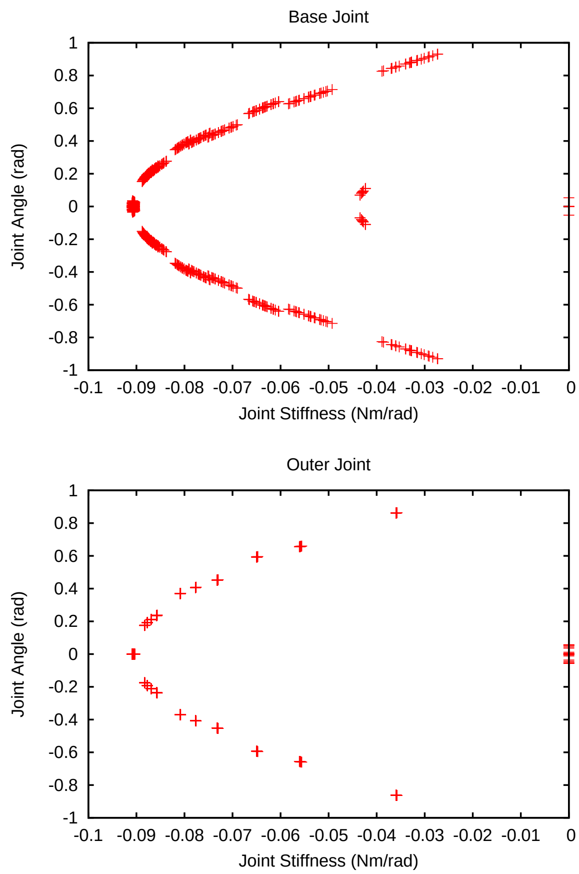

Fig. 8. Angles and stiffnesses of the base joint (top) and the outer joint (bottom) of the 2DOF arm with balanced muscles.

choosing the parameters for a muscle controlled system, the parameters responsible for the steady-state behavior of a joint can be chosen freely for the outermost joint, depending on the desired effort, movement range, and stiffness of the joint. As the parameters affect each other, some iterations of changing the parameters is to be expected in order to obtain the desired static performance.

Once the parameters have been set for the outermost joint, the choice of parameters for the preceding joints can be conducted in an inward manner, taking the disturbance from the outer joints into account. However, this applies to the static performance only, as it is the sole framework considered so far. A desire to obtain a specific dynamic performance should be preceded by further investigations of all relevant muscle parameters, that is, K_s, K_p, b, A, as well as x_{rest}, on the dynamic performance of the system. It is expected that such an investigation will find that dynamic performance can best be evaluated for the base joint first, followed by succeeding limbs.

IV. SIMPLE MUSCLE CONTROLLER

Having investigated how the different muscle parameters affect a muscle actuated system, it still needs to be investigated how such a system can be successfully controlled. As one of the simplest known controller structures is a linear controller, which has previously been used by [9] for control of pneumatic muscles, it would be a natural extension to investigate whether such a simple controller is sufficient for controlling the introduced muscle-actuated systems. The investigation of the performance of such a simple controller also opens up the possibility for further comparisons with more advanced controller structures in the future.

In order to control the system using a linear controller, an extension of the Proportional Position and Stiffness (PPS) controller, used in [9], is used. The extended control structure includes an offset term, thus allowing the relationship between the activation levels of the neurons to be merely affine. The controller structure is given by

$$\begin{bmatrix} \alpha_{flex} \\ \alpha_{ext} \end{bmatrix} = \begin{bmatrix} K_{off,f} & K_{\theta,f} & K_{k,f} \\ K_{off,e} & K_{\theta,e} & K_{k,e} \end{bmatrix} \begin{bmatrix} 1 \\ \theta \\ k \end{bmatrix} \quad , \qquad (3)$$

where θ is the desired angle of the system, k is the desired stiffness, and the α-values are the corresponding neural-activation signals for the muscles. The controller constants $K_{\theta,f}$, $K_{k,f}$, and $K_{k,e}$ are all positive whereas $K_{\theta,e}$ is negative. This is because a positive position error should result in a positive contribution to the flexion muscle as well as a negative contribution to the extension muscle, and vice versa. Also, as noted in [9], a positive stiffness error should increase activation in both muscles, and vice versa. The offset contributions $K_{off,f}$ and $K_{off,e}$ are included to put less restrictions on the linear controller, such that the non-linearities of the system can better be approximated. The set of optimal parameters for the linear controller can then be found using e.g., least squares.

For a symmetric system with no external disturbances, such as the 1DOF and 2DOF arms, the parameters are expected to be symmetric as well: $K_{\theta,f} = -K_{\theta,e}$, $K_{k,f} = K_{k,e}$, and $K_{off,f} = K_{off,e}$.

A. *Experimental Conditions*

For the experiments run on both the 1DOF and 2DOF arm, some common experimental conditions were used. For finding the controller parameters of Equation (3) a total of 150 random calibration tests were performed on each system. A random calibration was performed by applying a uniformly distributed activation level to each muscle of the given arm and storing the corresponding angle and stiffness values obtained once the system came to rest. Based on the obtained values, a least squares estimate of the desired linear controller parameters was obtained.

For evaluation of the performance of the obtained controller parameters, a total of 30 experiments was performed on each of the 1DOF and 2DOF systems. In order to obtain valid angle/stiffness goal combinations for the experiments, the methodology used when performing the calibration was followed to obtain these valid goals. For the experiments, the distribution of goals are thus similar to that of Fig. 4, where extreme angles are somewhat underrepresented. However, as such systems would primarily be expected to operate in non-

TABLE I

CONTROLLER PARAMETERS FOR THE PPS CONTROLLER FOR THE 1DOF ARM.

	K_{off}	K_θ	K_k
Flexor	0.530	0.543	0.360
Extensor	0.521	-0.633	0.276

TABLE II

PERFORMANCE OF THE PPS CONTROLLER FOR 30 TARGETS USING THE 1DOF ARM.

Parameter	Avg. Err.	Std. Dev.
θ	$1.18 \cdot 10^{-2} rad$	$8.92 \cdot 10^{-3} rad$
k	$8.52 \cdot 10^{-4} Nm/rad$	$9.76 \cdot 10^{-4} Nm/rad$

extreme ranges, evaluating the performance based on such goals is not considered to be problematic.

B. 1DOF Arm

The controller parameters obtained when calibrating the 1DOF system are listed in Table I. It can be seen that the expected symmetries of the parameters are not exact, but the values are so close that they will balance each other out in most situations as if the system was totally symmetric. The cause for the deviation is the randomness of the points used in the calculation of the controller parameters.

The results obtained when performing 30 experiments on the system, using the parameters given in Table I, are summarized in Table II. It should be noted that all of the tests were kept within a range of $[-0.662; 0.625]$ for the angles and $[-9.08 \cdot 10^{-2}; -4.23 \cdot 10^{-2}]$ for the stiffnesses. Thus, some of the large non-linearities near the extremes were, as expected, not included in the tests. Nonetheless, within the tested range, the obtained results show that the linear PPS controller is quite capable of accurately controlling the muscle-actuated system.

C. 2DOF Arm

The controller parameters obtained when performing calibration using 150 random calibration tests on the 2DOF system are shown in Table III. As was the case for the 1DOF arm, the symmetries of the parameters can also be seen for the 2DOF arm. However, it is also worth noting how different the parameters for the base and the outer joints are. This is due to both the effects of the cross couplings in the system as well as the fact that the muscles for the outer joint have double the length of those actuating the base joint.

TABLE III

CONTROLLER PARAMETERS FOR THE PPS CONTROLLER FOR THE 2DOF ARM.

	K_{off}	K_θ	K_k
Flexor_{base}	0.622	0.591	1.597
Extensor_{base}	0.642	-0.594	1.826
Flexor_{outer}	0.271	0.610	-2.893
Extensor_{outer}	0.272	-0.594	-2.898

TABLE IV

PERFORMANCE OF THE PPS CONTROLLER FOR 30 TARGETS USING THE 2DOF ARM.

Parameter	Avg. Err.	Std. Dev.
θ_{base}	$1.09 \cdot 10^{-2} rad$	$7.86 \cdot 10^{-3} rad$
k_{base}	$7.26 \cdot 10^{-4} Nm/rad$	$8.93 \cdot 10^{-4} Nm/rad$
θ_{outer}	$6.23 \cdot 10^{-3} rad$	$9.71 \cdot 10^{-3} rad$
k_{outer}	$6.81 \cdot 10^{-3} Nm/rad$	$2.28 \cdot 10^{-2} Nm/rad$

The results when testing the parameters of Table III in 30 experiments on the 2DOF system are summarized in Table IV. When comparing the results for the base joint to the results of the 1DOF system, the errors of the 2DOF system are in fact a little smaller and have lower standard deviations. It is also evident that the average error for the angle of the outer joint is smaller than that for the inner joint. It should be noted though that despite the smaller average error, the standard deviation is also significantly larger. For the stiffness, the average error of the outer joint is actually worse than that for the inner joint and the standard deviation is higher. Thus, keeping in mind that the test points were mainly located in non-extreme regions, the performance of the linear PPS controller for this non-linear 2DOF system was found to be quite good.

V. CONCLUSION

This paper has investigated how artificially simulated muscles, based on the Hill-type muscle model, depend on the settings of the various parameters of the model. Three different parameters were investigated, the muscle rest length, the serial spring element, and the parallel spring element. The muscle rest length was found to influence both the range of obtainable angles and stiffnesses. In fact, based on the setting of the muscle rest length, the system could even be brought into unstable equilibrium points or even given angles with a corresponding stiffness value of 0. The serial spring element was found to only influence the stiffness of the system, as the range of obtainable angles did not change with varying values for this parameter. The parallel spring element had a significant effect on both the range of obtainable angles and the stiffnesses obtainable by the system. In order to obtain a certain performance characteristic of a muscle controlled system, a recommended procedure would thus be to tune the parameters in the following order:

1) Rest length x_{rest} based on energy considerations
2) Parallel spring constant K_p to obtain desired angle range
3) Serial spring constant K_s to adjust to desired stiffness range

This should assure that the static performance of the system under consideration matches the desired one.

Aside from investigating the basic muscle parameters, it was also investigated how well a simple linear controller could control both a non-linear 1DOF as well as a non-linear 2DOF muscle controlled system. Despite the non-linearities, and the fact that the extremes of the system were underrepresented in the tests, the linear control of both systems yielded quite good results. Thus, when considering only static performance, a linear controller would be more than adequate for controlling a muscle based system as long as the requirements for precision are not stricter than $1.5 \cdot 10^{-2} rad$ on the angle and $2.5 \cdot 10^{-2} Nm/rad$ for the stiffness, and as long as the system is largely operated in non-extreme regions.

While the insights provided in this paper may be used to guide parameter choices and the design of a basic controller, future work should focus on optimizing the control parameters further and on coupling the basic muscle control strategy with more advanced control methods. In biological systems, it still remains unclear which muscle parameters are actually controlled. For example, the elaborate tendon system, apart from the muscle morphology itself, may indirectly realize the manipulation of other, possibly macro-muscle parameters. Our study shows that the possibility to vary K_s in a given muscle system directly allows the manipulation of joint stiffnesses while hardly affecting joint angles. Possibly, the gamma motor-neuron may have similar effects in biological muscle systems. Future research may design more flexible, human-like robotic systems based on such muscle control insights, in which the neural control challenge may be further eased due to available (macro) muscle control parameters given a well-designed muscle morphology.

VI. ACKNOWLEDGMENTS

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