

A Bio-inspired Approach for Regulating and Measuring Visco-elastic Properties of a Robot Arm

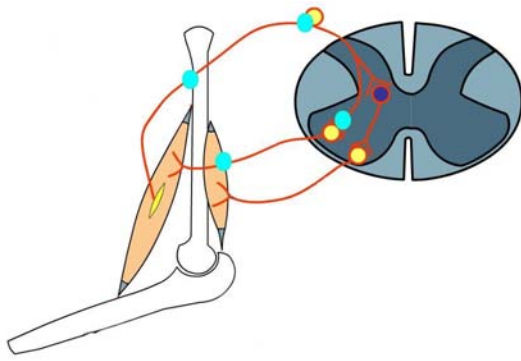


Figure 1: Spindle responses with and without gamma drive during active contraction in the monosynaptic stretch reflex. Gamma motor neurons (light blue circles in the figure) innervate spindles and in mammals are controlled separately from alpha motoneurons (yellow circles), thereby allowing control of the sensitivity of the muscle spindles. When there is active contraction of alpha motoneurons but not gamma the muscle shortens and silences the spindle. When there is active contraction of alpha and gamma the fiber ends contract and maintain the spindle sensitivity. This is called alpha/gamma coactivation.

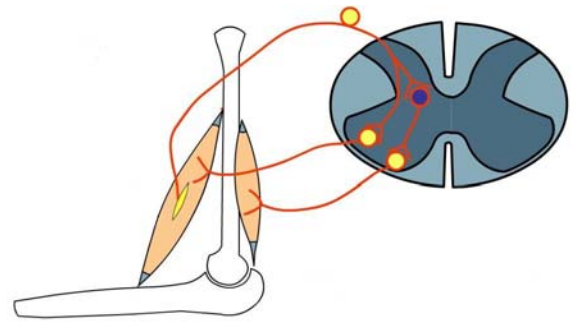


Figure 2: Muscle contraction during the monosynaptic stretch reflex. The monosynaptic stretch reflex is activated by spindle I alpha afferents. When the muscle lengthens the muscle spindle, which is a receptor or sensor of the muscle sensitive to stretch, is stretched and firing rate of I-alpha fibers increases. This increases alpha motor neuron activity (yellow circles in the figure). The muscle contracts and its length decreases.

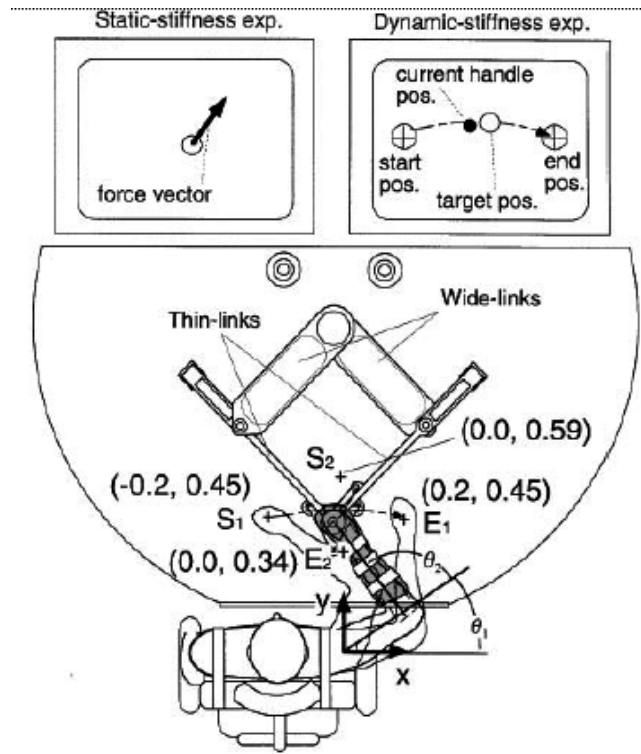


Figure 3: Experimental setup for measuring human arm stiffness (taken from [29]).

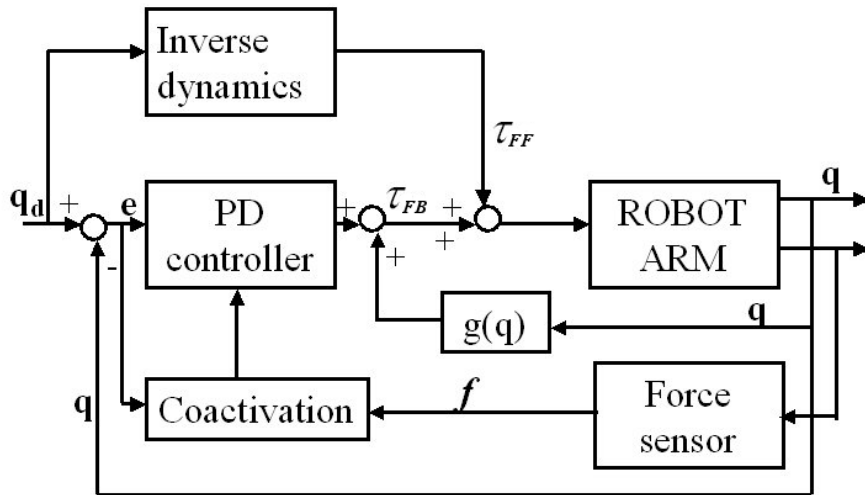


Figure 4: Feedforward plus feedback control scheme.

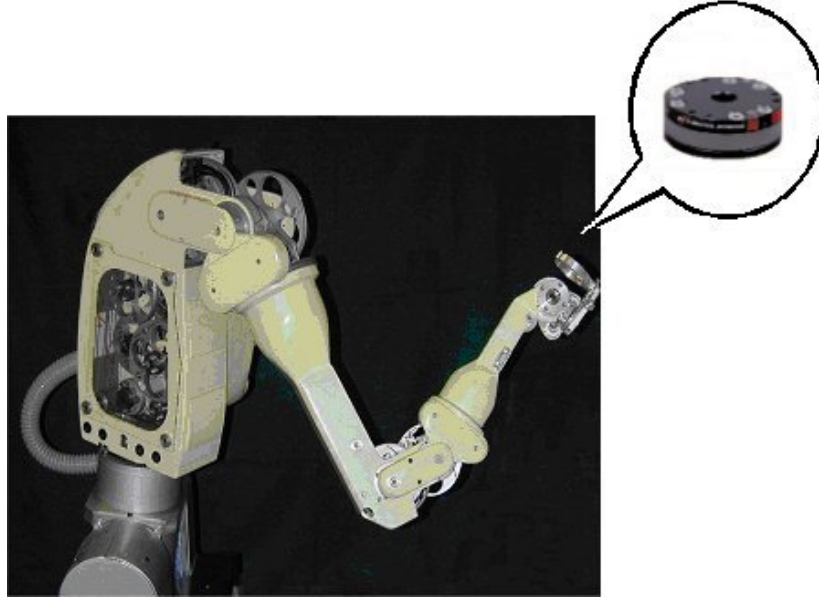


Figure 5: Experimental setup for validating the coactivation-based compliance control in the joint space. The Dexter arm and the six-axis force sensor are shown.

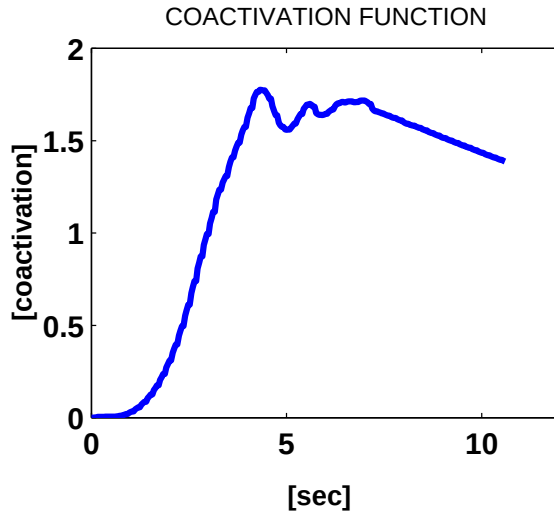


Figure 6: Coactivation function in the free space.

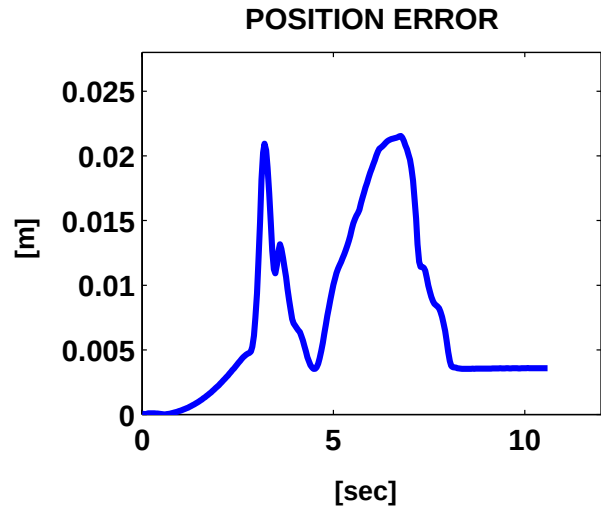


Figure 7: Position error in the free space.

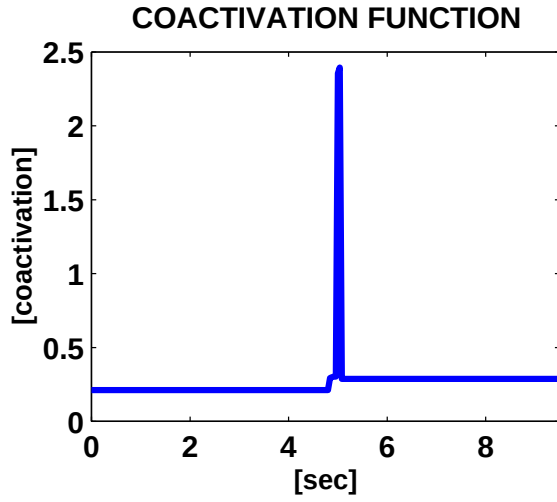


Figure 8: Coactivation function in the constrained motion.

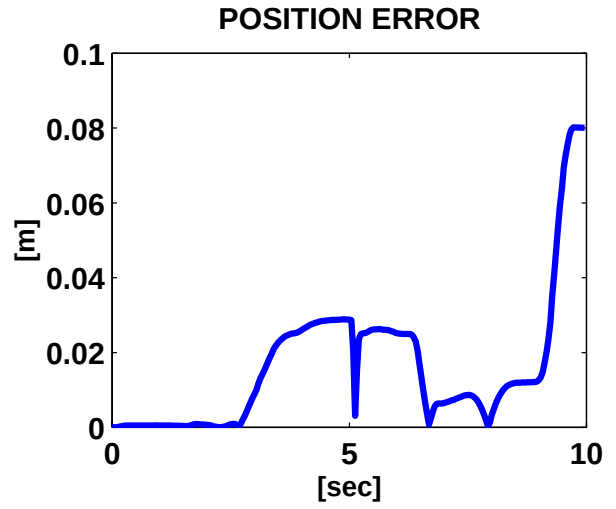


Figure 9: Position error in the constrained motion.

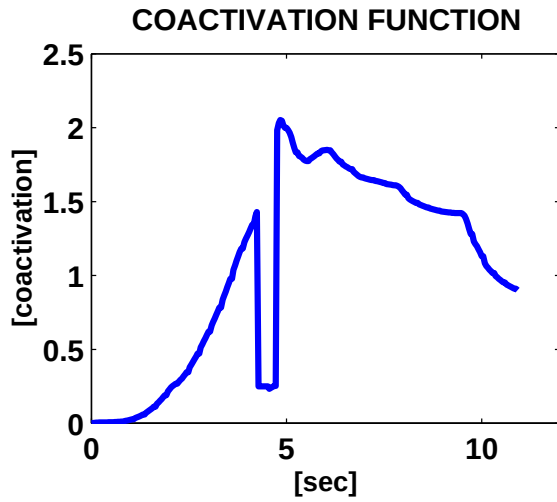


Figure 10: Coactivation function in the transition from the free space to the constrained space and return to the free space.

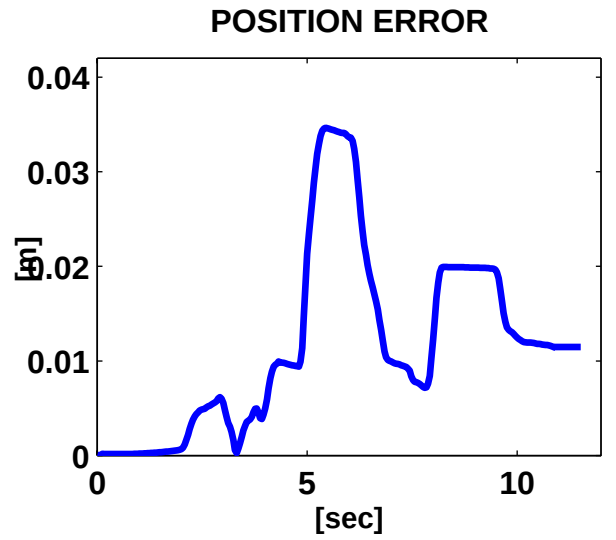


Figure 11: Position error in the transition from the free space to the constrained space and return to the free space.

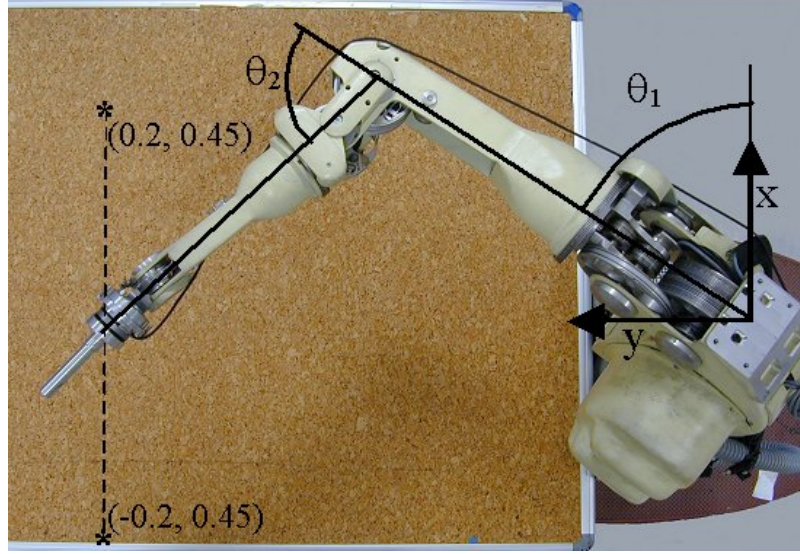


Figure 12: Experimental setup for measuring stiffness in a robot arm (Plane view).

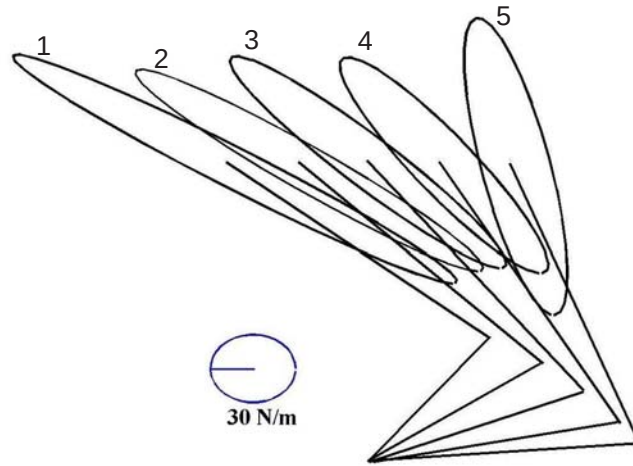


Figure 13: Stiffness ellipses during posture maintenance when compliance control in the joint space is used ($K_P = \text{diag}\{32, 4.5\}$).

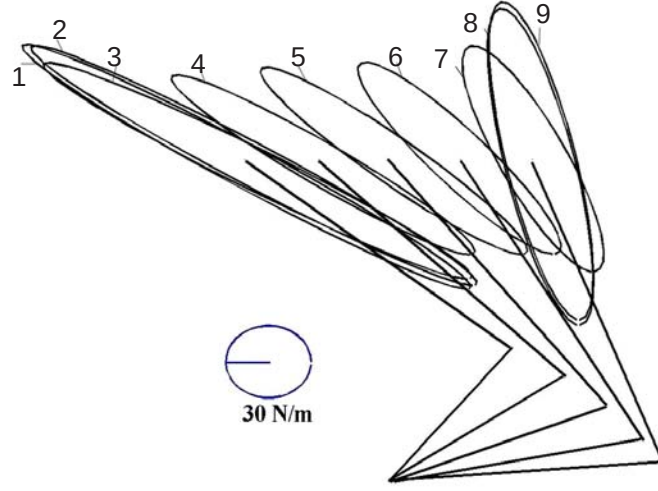


Figure 14: Stiffness ellipses during point-to-point motion when compliance control in the joint space is used ($K_P = \text{diag}\{32, 4.5\}$).

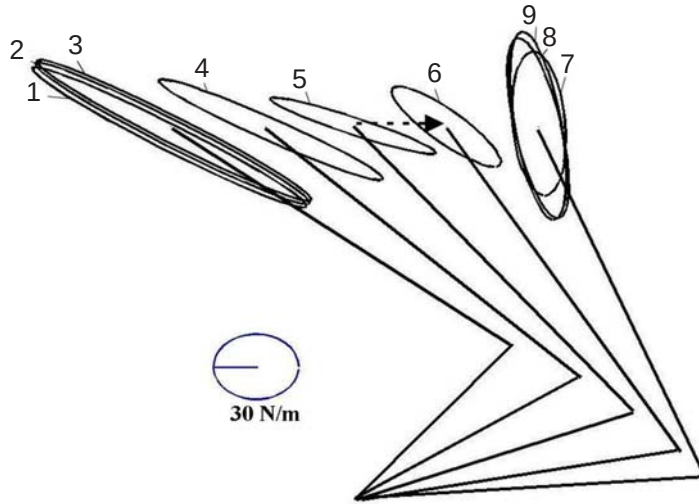


Figure 15: Stiffness ellipses during constrained motion when compliance control in the joint space is used ($K_P = \text{diag}\{15, 2.5\}$).

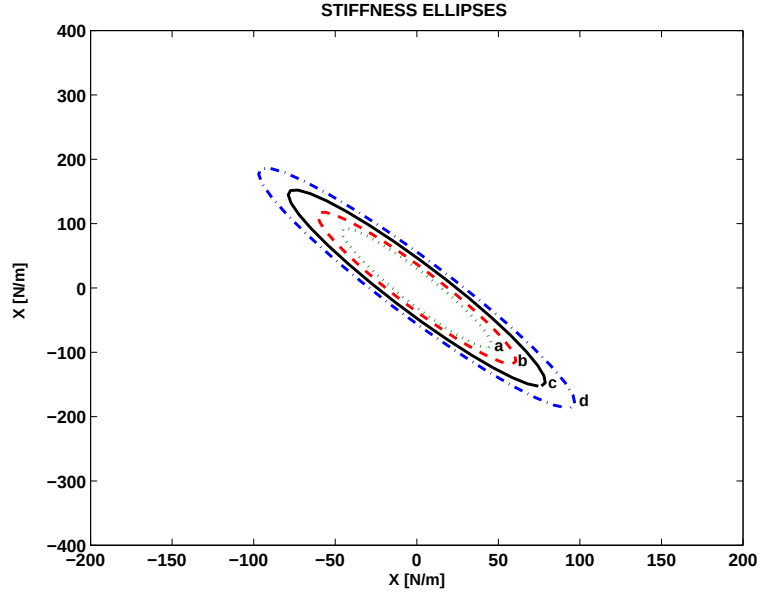


Figure 16: Stiffness ellipses during posture maintenance for $K_P = \text{diag}\{15, 2.5\}$ (a), $K_P = \text{diag}\{20, 3\}$ (b), $K_P = \text{diag}\{26, 3.8\}$ (c) and for $K_P = \text{diag}\{32, 4.5\}$ (d) (Posture 3).

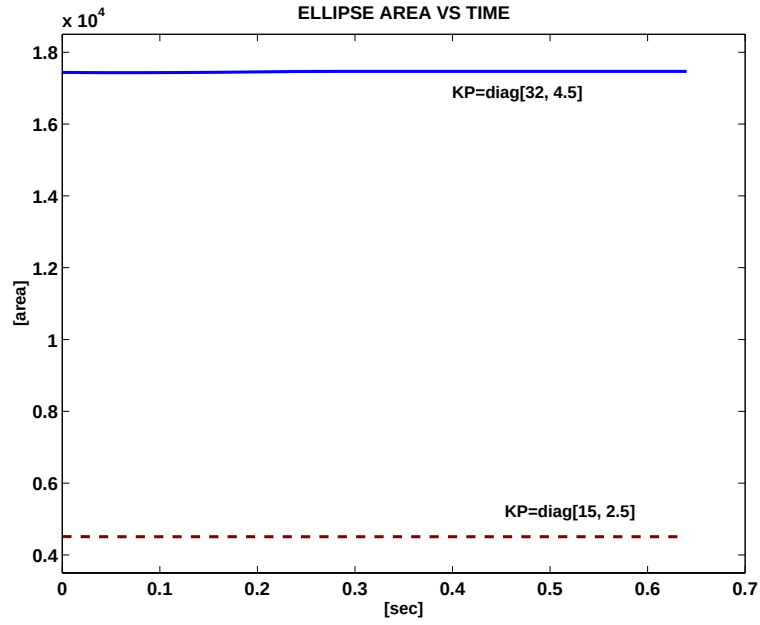


Figure 17: Area over time during point-to-point motion for $K_P = \text{diag}\{15, 2.5\}$ (a) and for $K_P = \text{diag}\{32, 4.5\}$ (b).

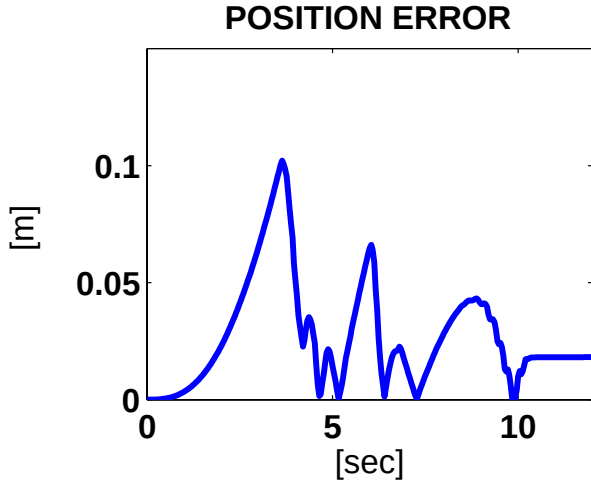


Figure 18: Position error when compliance control in the joint space is used ($K_P = \text{diag}\{32, 4.5\}$).

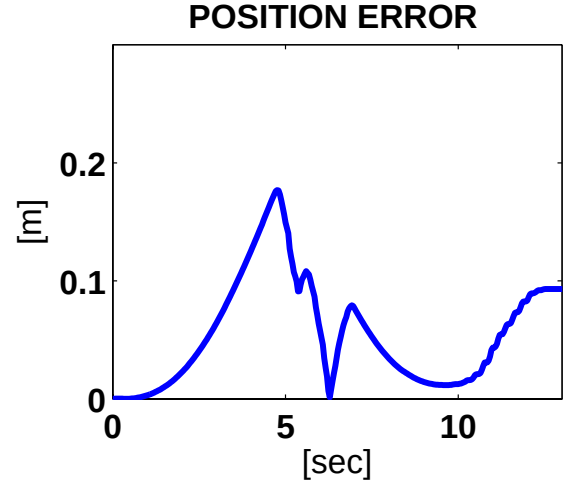


Figure 19: Position error when compliance control in the joint space is used ($K_P = \text{diag}\{15, 2.5\}$).

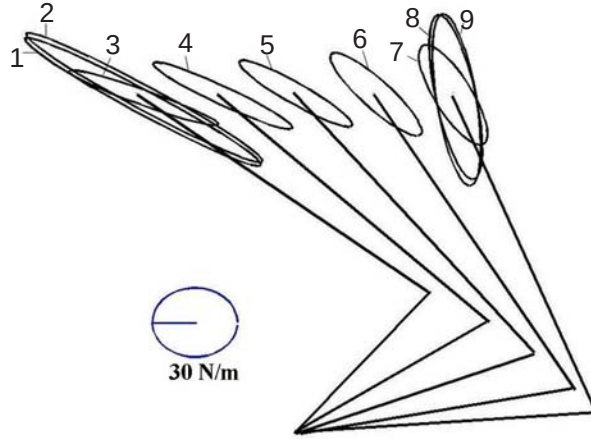


Figure 20: Stiffness ellipses during point-to-point motion when compliance control in the joint space is used ($K_P = \text{diag}\{15, 2.5\}$).

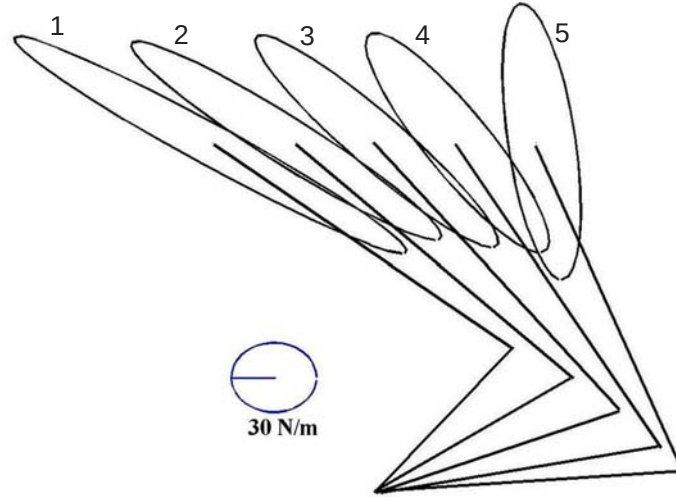


Figure 21: Stiffness ellipses during posture maintenance when coactivation-based compliance control in the joint space is used ($\alpha = 1$).

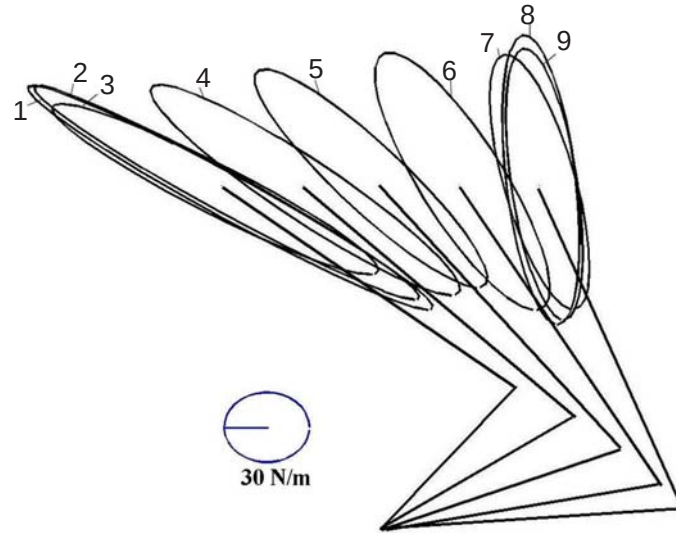


Figure 22: Stiffness ellipses during point-to-point motion when coactivation-based compliance control in the joint space is used ($\alpha = 1$).

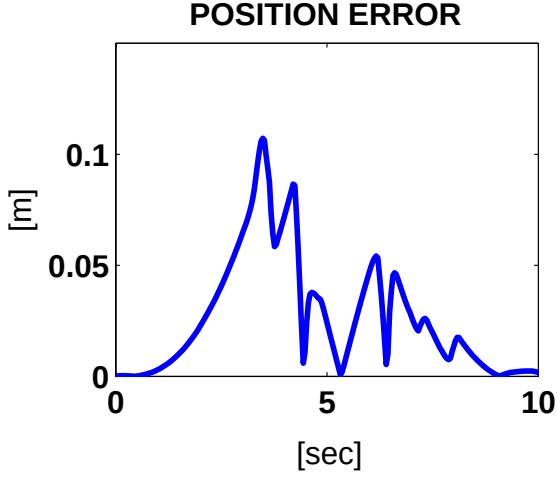


Figure 23: Position error when coactivation-based compliance control in the joint space is used ($\alpha = 1$).

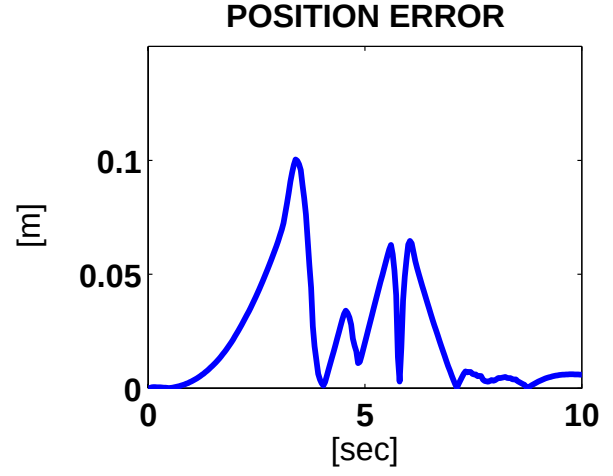


Figure 24: Position error when coactivation-based compliance control in the joint space is used ($\alpha = 2$).

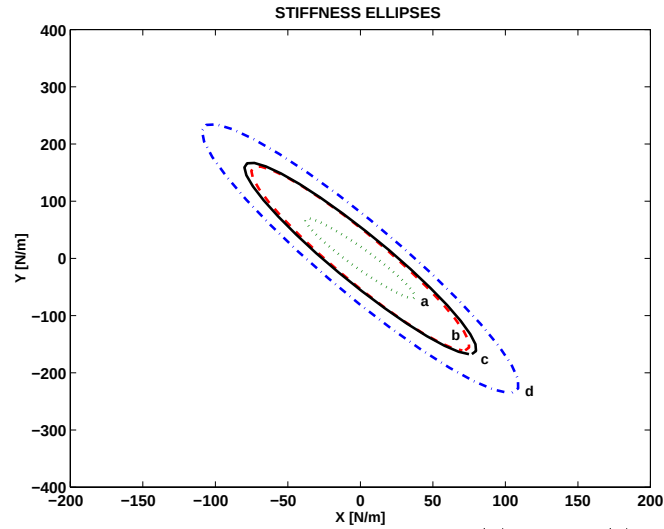


Figure 25: Stiffness ellipses during posture maintenance for $\alpha = 0.5$ (a), $\alpha = 1$ (b), $\alpha = 1.5$ (c) and for $\alpha = 2$ (d) (Posture 3).

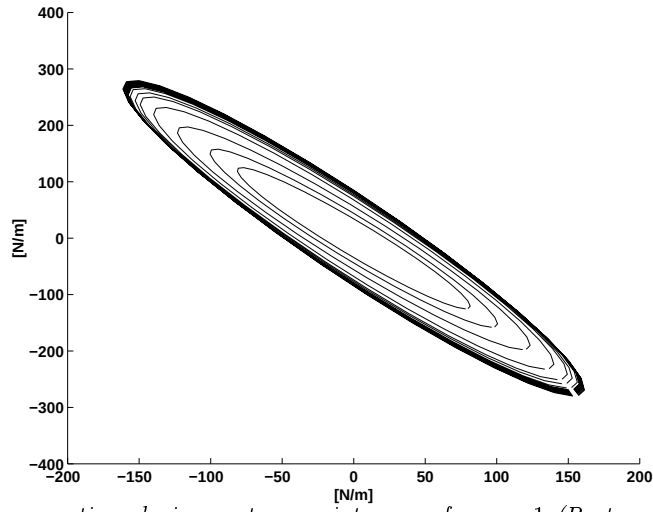


Figure 26: Stiffness ellipses over time during posture maintenance for $\alpha = 1$ (Posture 3). The ellipse area increases over time.

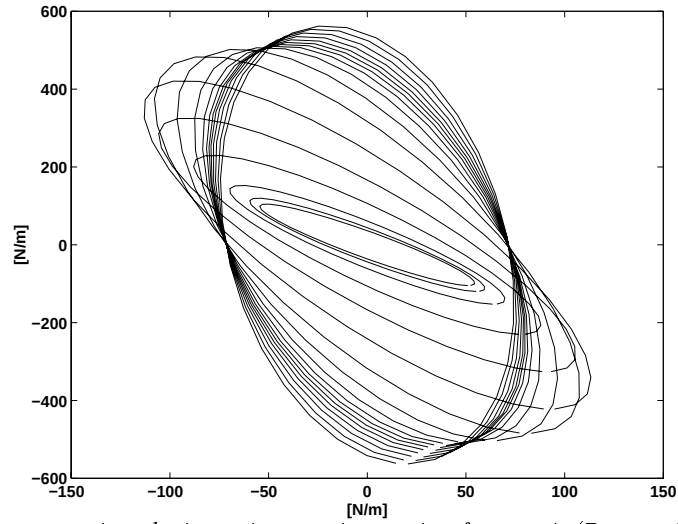


Figure 27: Stiffness ellipses over time during point-to-point motion for $\alpha = 1$ (Posture 5). The ellipse area increases and the orientation changes by rotating towards the next position.

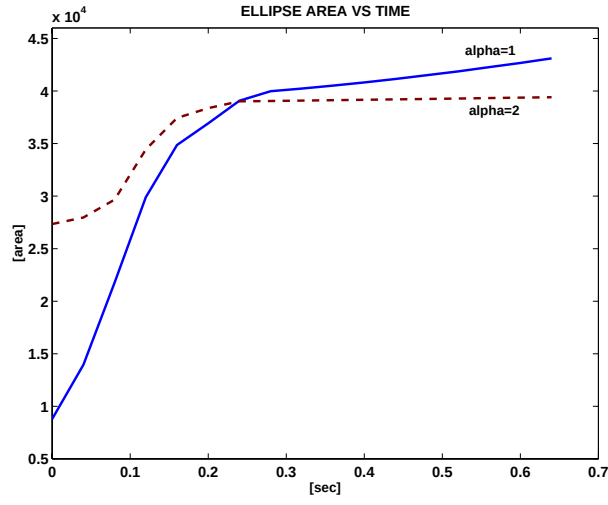


Figure 28: Area over time during point-to-point motion for $\alpha = 1$ (a) and for $\alpha = 2$ (b).

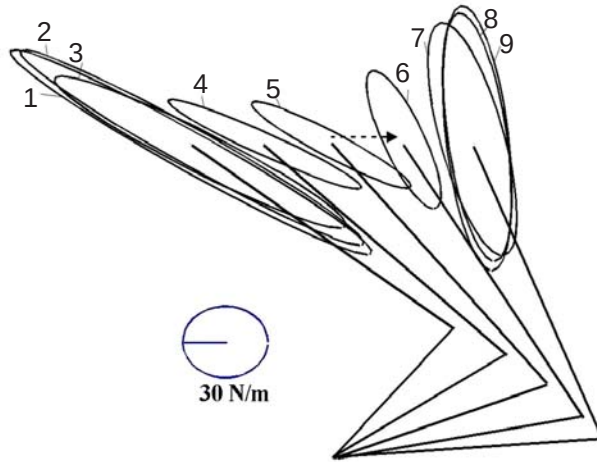


Figure 29: Stiffness ellipses during constrained motion when coactivation-based compliance control in the joint space is used ($\alpha = 1$).