# Table Tennis Simulation Report

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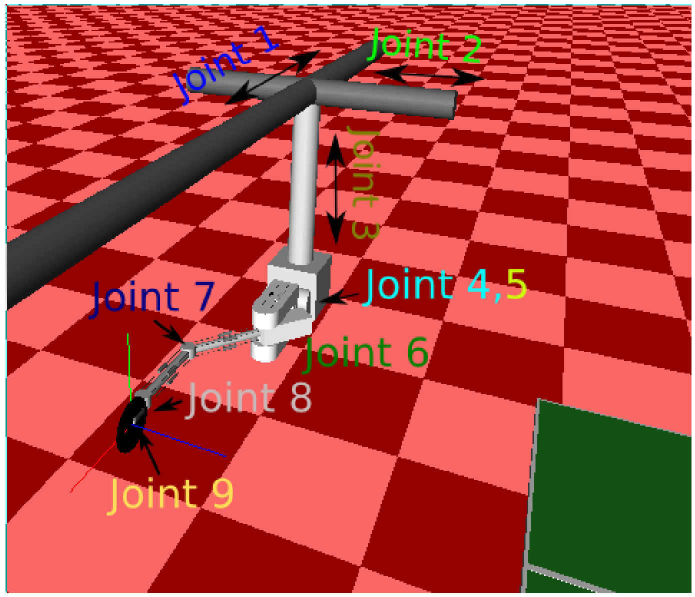
**Abstract**

This document contains a brief description about the table tennis setup in the SL-simulator and presents the requirements found by simulation for the BioRob setup.

## 1 Setting for the BioRob

In our simulation the BioRob is mounted on 3 linear axis which allows the base of the BioRob to move in each dimension. After the linear axis, we added an additional shoulder joint which allows spherical shoulder movements. The exact setup is depicted in Figure 1. After this shoulder joint we mounted a standard BioRob in simulation. The BioRob is mounted to the left side of a base such that the elbow joints can perform the main part of the hitting movement. In this report we will test which of the joints are necessary in oder to probably play table tennis. We will evaluate the setup without the 3rd linear axis (Z-axis), without the last wrist joint, without the additional shoulder joint. All scenarios are evaluated for a forehand and a backhand movement. We evaluated the success-rate for hitting the ball, the deviation from the desired target on the opponents table, the maximum joint displacement, the maximum joint accelerations and the maximum torques (forces) needed for the movements. This evaluation is done for different hitting positions and targets (both on the X-axis). Each hitting-position/target combination is repeated for 20 times with some noise on the ball-cannon in order to get proper statistics. In our plots, the 1st three joints correspond to the linear axis, and joint 4-9 to the angular joints (starting with the additional shoulder joint).

The table tennis controller uses a model-based approach to calculate the trajectories. Note that this controller is not perfect as it uses an imperfect model of the ball. The performance is likely to be improved by applying learning methods. The controller assumes a reaction time for hitting the ball (time from detecting the ball and predicting its trajectory to hitting the ball) of $0.55s$. Larger reaction times lead to smaller accelerations, however, a reaction time of $0.55s$ is already quite large.




(a) BioRob

Figure 1: Simulation of the table tennis setup with the BioRob. We use 3 linear axis and one rotational joint (Joint 4) as base for the BioRob.

Table 1: Standard Model. SuccessRates

| | Success rate | Valid Region |
|---|---|---|
| Forehand : | 0.66 | [-0.30 0.50] |
| Backhand : | 0.64 | [-0.30 0.50] |

## 2 Standard Model (No Z-axis) (70 cm above table)

The standard setup is without linear Z-axis and the biorob is mounted 70 cm above the table. The mean successrates of this model with forehand and backhand as well as the valid areas can be seen in Table 1. The valid area is defined as all hitting movements where the acceleration of the linear axis is below $20ms^-2$ and of the rotational joints below $120rad/s^2$.(ToDO: Is this too much ?) The maximum joint positions, accelerations and torques for all evaluated (valid) trials can be seen in Table 2 for the forehand hitting and in Table 3.

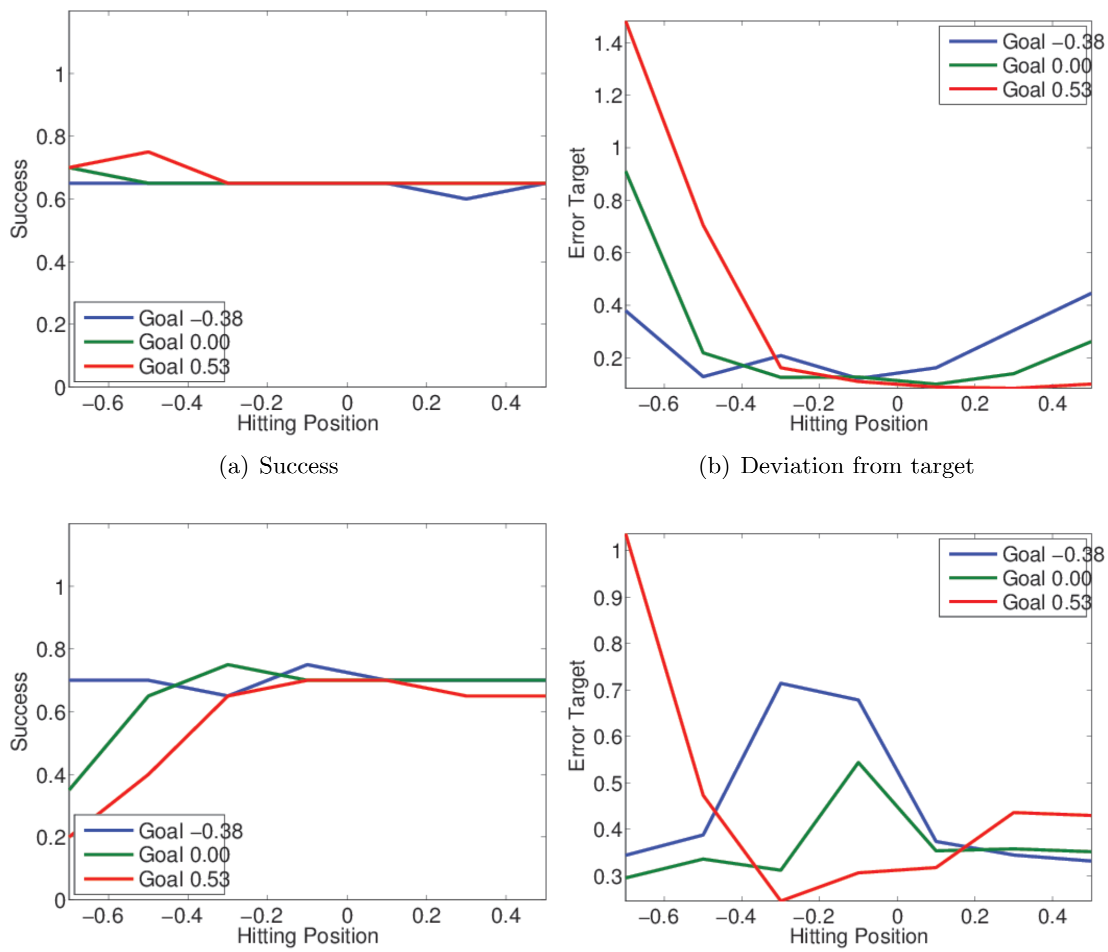
The evaluations can be seen in Figure **??** to **??** for the forehand hitting movement and backhand hitting movement.

Table 2: Joint Specifcations for standard scenario (70 cm above table). Forehand

| Joint | Max Acc | Min Pos | Max Pos | Max Vel | Max Torque |
|---|---|---|---|---|---|
| 1 | 16.11 | -0.80 | -0.32 | 1.88 | 87.55 |
| 2 | 3.22 | -0.01 | 0.06 | 0.34 | 23.74 |
| 3 | 1.02 | -0.25 | -0.25 | 0.02 | 53.99 |
| 4 | 23.23 | 0.58 | 1.14 | 2.28 | 34.14 |
| 5 | 27.04 | -0.00 | 0.16 | 0.71 | 3.13 |
| 6 | 76.38 | -0.17 | 1.21 | 4.15 | 6.27 |
| 7 | 123.26 | -0.80 | -0.08 | 6.43 | 7.33 |
| 8 | 111.30 | -0.00 | 0.47 | 2.00 | 1.08 |
| 9 | 8.76 | -0.00 | 0.37 | 1.28 | 0.80 |

Table 3: Joint Specifcations for standard scenario (70 cm above table). Backhand

| Joint | Max Acc | Min Pos | Max Pos | Max Vel | Max Torque |
|---|---|---|---|---|---|
| 1 | 20.57 | -0.50 | 0.41 | 3.33 | 116.65 |
| 2 | 8.43 | -0.00 | 0.26 | 1.00 | 62.12 |
| 3 | 1.93 | -0.25 | -0.25 | 0.05 | 72.82 |
| 4 | 46.03 | 0.24 | 0.81 | 3.39 | 36.05 |
| 5 | 61.37 | -0.87 | 0.12 | 4.92 | 6.75 |
| 6 | 106.30 | -1.45 | -0.30 | 6.80 | 17.28 |
| 7 | 122.00 | -1.18 | -0.14 | 7.43 | 10.58 |
| 8 | 54.64 | -0.81 | 0.00 | 6.09 | 3.88 |
| 9 | 31.74 | -0.89 | 0.07 | 4.03 | 2.52 |



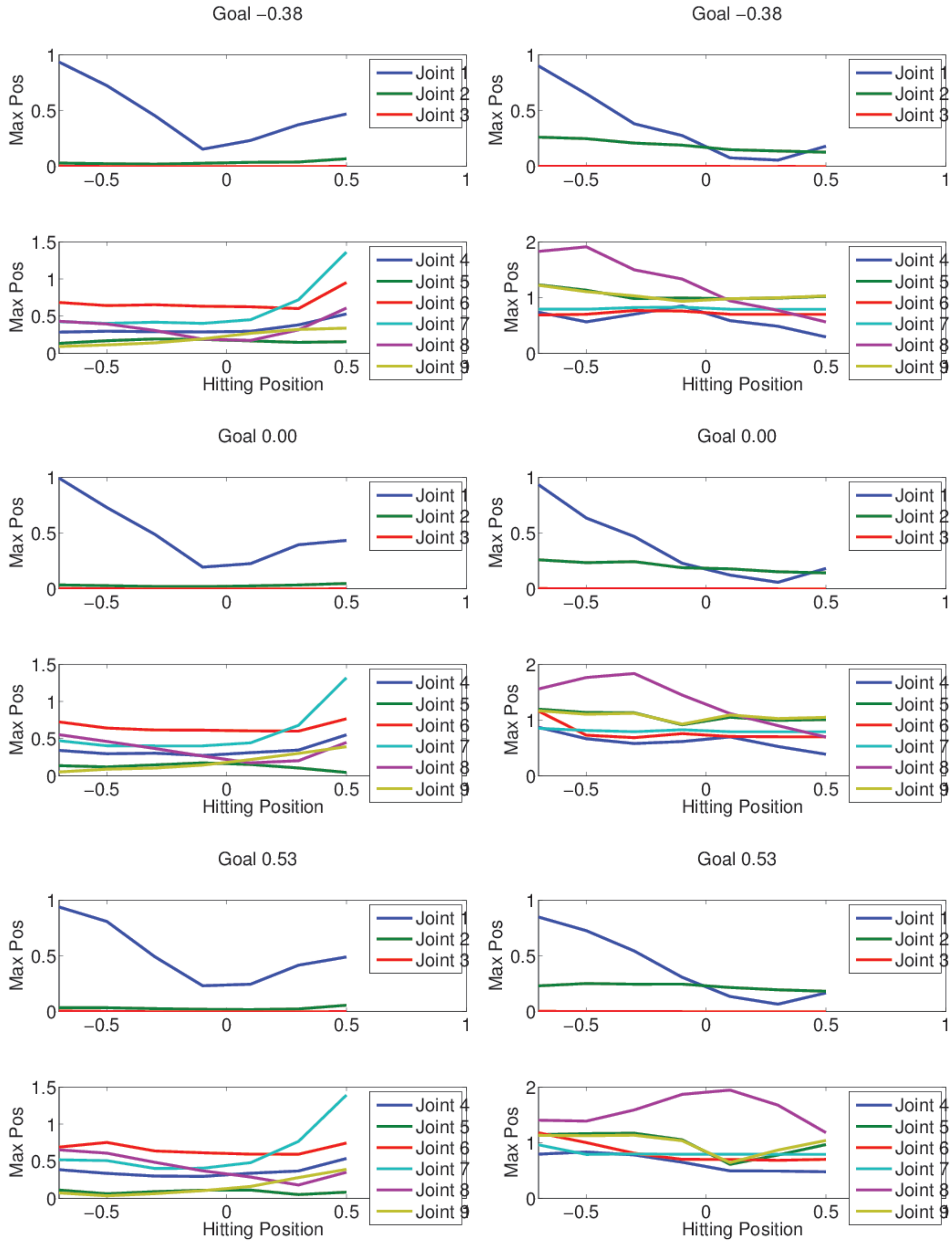

(a) Success

(b) Deviation from target

(c) Success (Backhand)

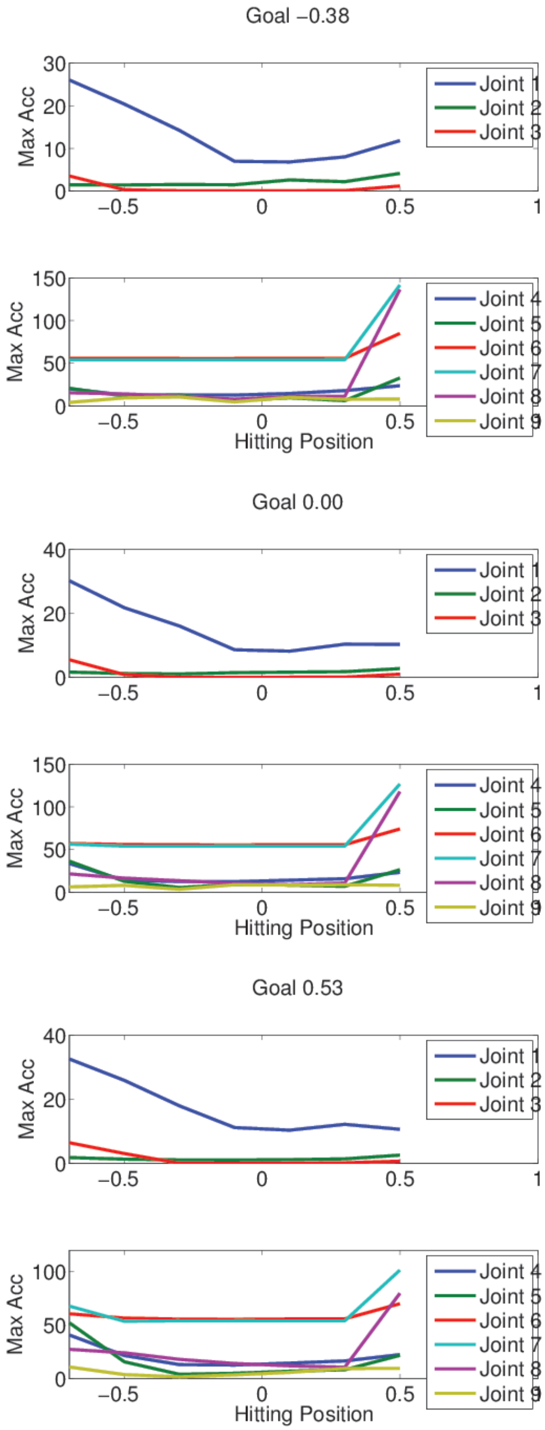
(d) Deviation from target (Backhand)

Figure 2: Standard Model (70cm) : (a) Success rate and (b) deviation from target for 3 different desired targets (point of impact of the ball on the opponents side). The robot needs to hit the ball at different locations. (c-d) same thing for the backhand

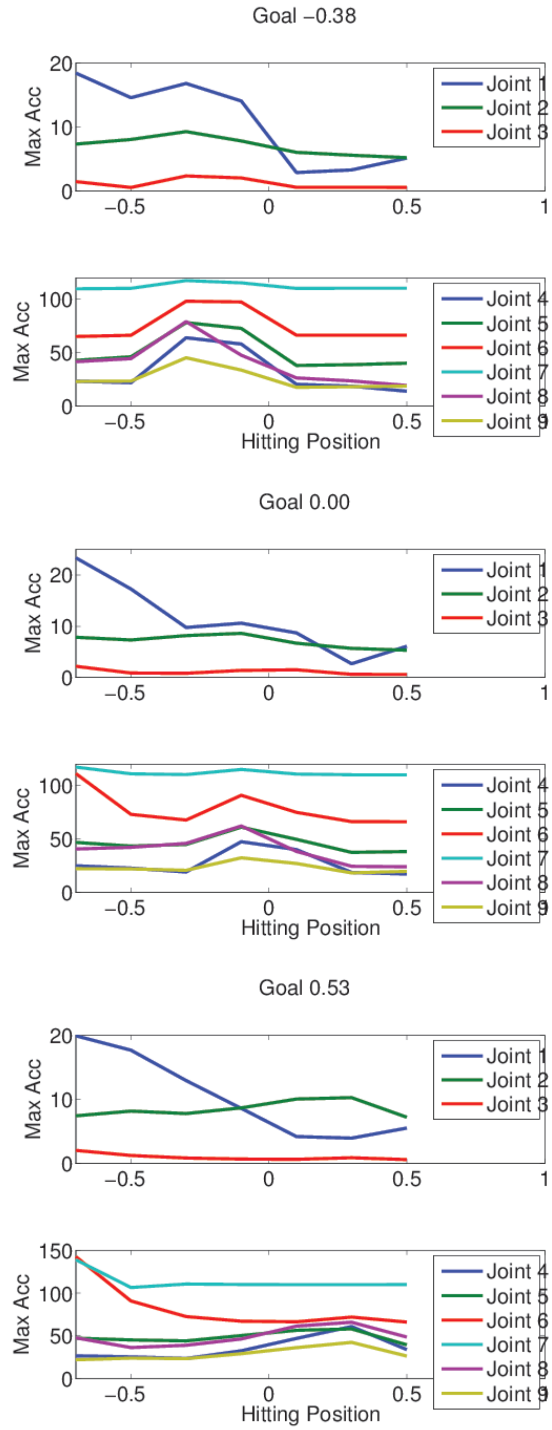



(e) ForeHand (f) BackHand

Figure 3: Standard Model (70cm) : Maximum joint deviation from initial position for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

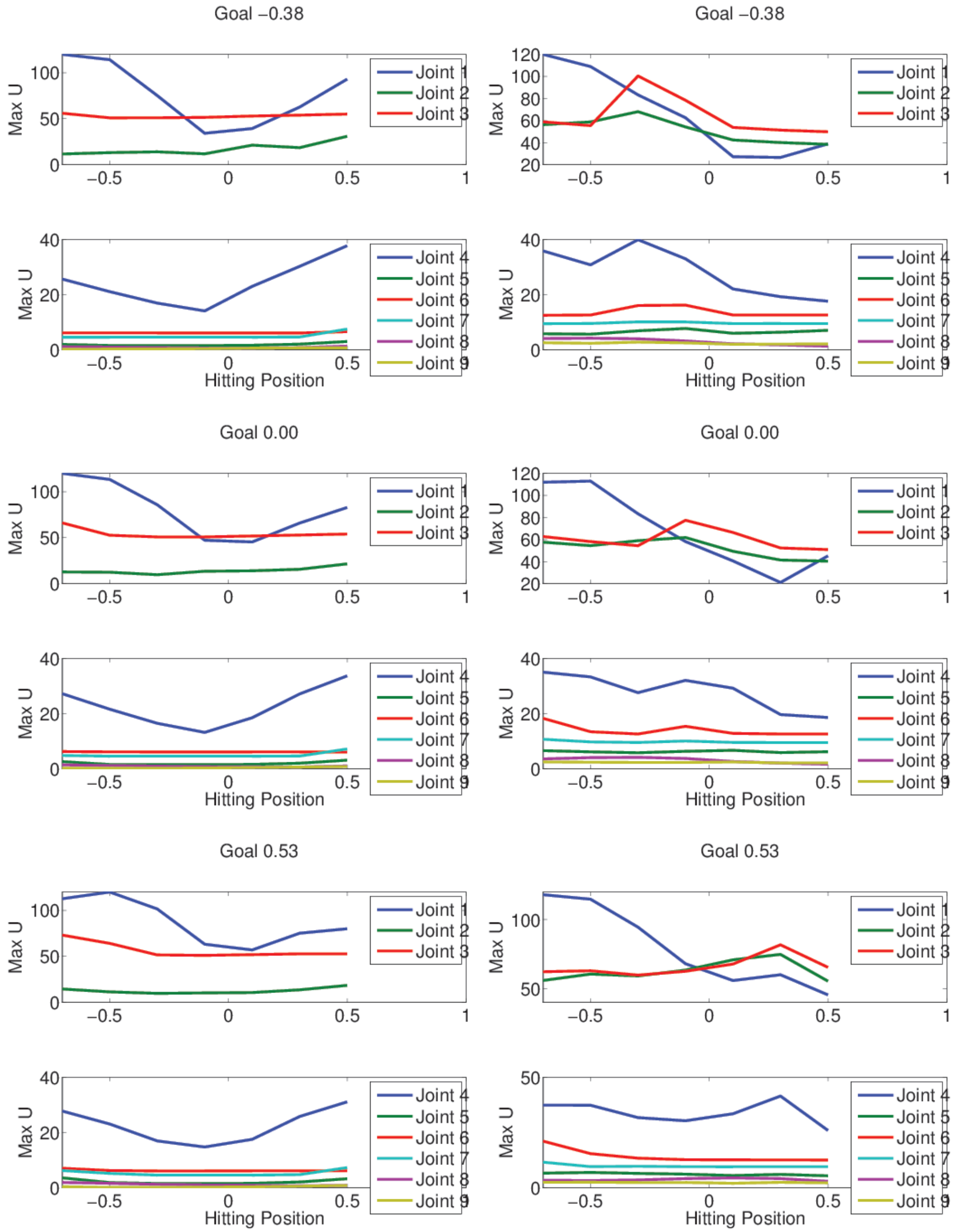



(e) ForeHand




(f) BackHand

Figure 4: Standard Model (70cm) : Maximum joint acceleration for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand




(e) ForeHand (f) BackHand

Figure 5: Standard Model : Maximum torques for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

Table 4: Standard Model. SuccessRates

| | Success rate | Valid Region |
|---|---|---|
| Forehand : | 0.62 | [-0.70 0.30] |
| Backhand : | 0.72 | [-0.10 0.50] |

Table 5: Joint Specifcations for standard scenario (15 cm above table). Forehand

| Joint | Max Acc | Min Pos | Max Pos | Max Vel | Max Torque |
|---|---|---|---|---|---|
| 1 | 18.38 | -0.80 | -0.11 | 2.57 | 110.53 |
| 2 | 2.32 | -0.00 | 0.03 | 0.16 | 17.10 |
| 3 | 0.36 | -0.80 | -0.80 | 0.01 | 59.17 |
| 4 | 17.41 | -0.03 | 0.30 | 1.85 | 26.68 |
| 5 | 22.81 | -0.00 | 0.53 | 2.05 | 3.14 |
| 6 | 55.71 | -0.28 | 1.03 | 4.92 | 8.63 |
| 7 | 54.19 | -0.80 | -0.07 | 3.76 | 4.79 |
| 8 | 16.98 | -0.00 | 0.50 | 1.85 | 1.10 |
| 9 | 16.96 | -0.00 | 0.30 | 1.62 | 1.01 |

# 3 Standard Model (No Z-axis) (15 cm above table)

All other models were evaluated where the Biorob was mounted 15cm above the table. The mean successrates of this model with forehand and backhand as well as the valid areas can be seen in Table 4. The valid area is defined as all hitting movements where the acceleration of the linear axis is below $20ms^-2$ and of the rotational joints below $120rad/s^2$.(ToDO: Is this too much ?) The maximum joint positions, accelerations and torques for all evaluated (valid) trials can be seen in Table 5 for the forehand hitting and in Table 6.

The evaluations can be seen in Figure 6 to 9 for the forehand hitting movement and backhand hitting movement.

# 4 No Spherical Shoulder, move Z-Axis

In this model we disabled the linear axis for the Z-direction (up/down). The mean successrates of this model with forehand and backhand as well as the valid areas can be seen in Table 7. The maximum joint positions, accelerations and torques for all evaluated (valid) trials can be seen in Table 8 for the forehand hitting and in Table 9.

The evaluations for different hitting-points and goals can be seen in Figure 10 to 13 for the forehand hitting movement and backhand hitting movement.

Table 6: Joint Specifcations for standard scenario (15 cm above table). Backhand

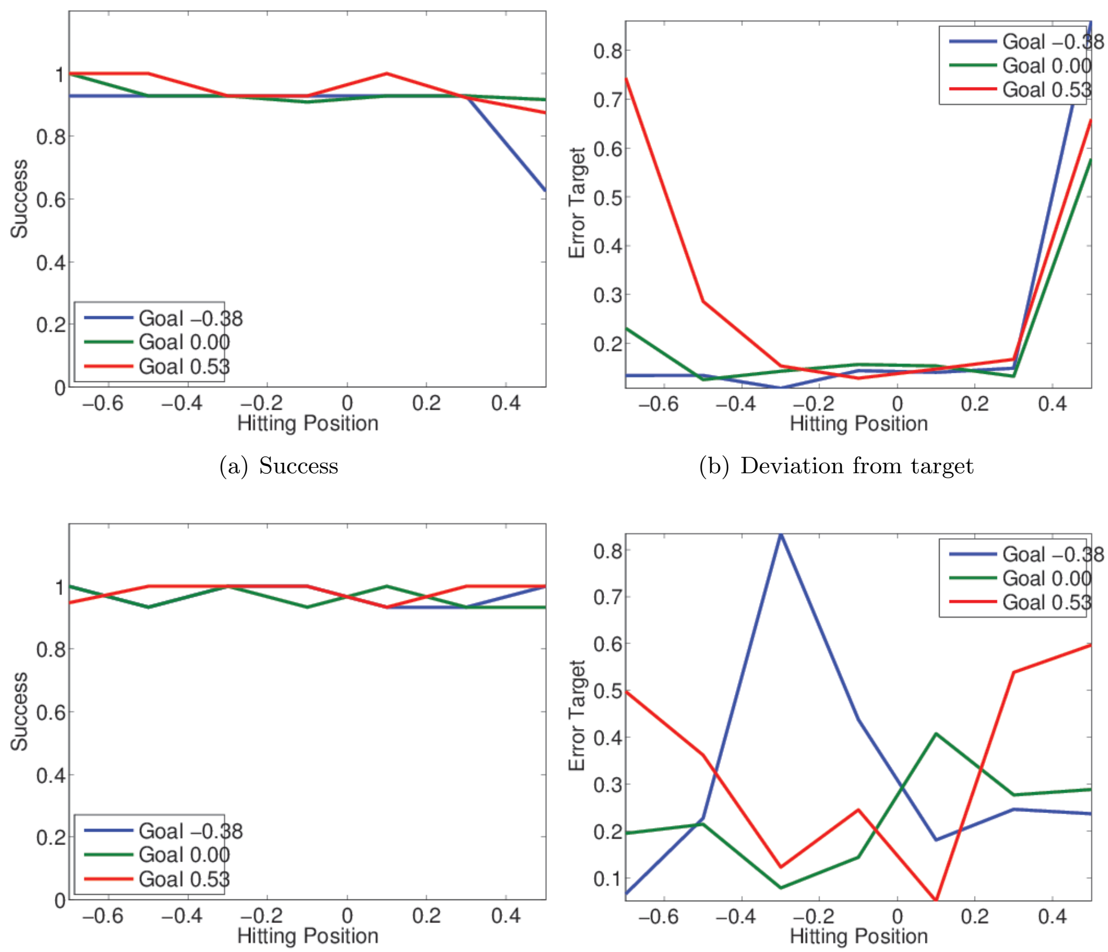
| Joint | Max Acc | Min Pos | Max Pos | Max Vel | Max Torque |
|---|---|---|---|---|---|
| 1 | 12.36 | -0.50 | -0.21 | 1.33 | 106.85 |
| 2 | 5.13 | -0.03 | 0.07 | 0.52 | 41.33 |
| 3 | 2.12 | -0.80 | -0.80 | 0.05 | 119.11 |
| 4 | 85.93 | -0.16 | 0.97 | 6.37 | 54.89 |
| 5 | 37.31 | -0.01 | 0.48 | 2.54 | 6.11 |
| 6 | 76.54 | -1.45 | -0.32 | 4.55 | 12.05 |
| 7 | 112.52 | -1.48 | 0.27 | 8.08 | 9.84 |
| 8 | 64.83 | -0.80 | 0.04 | 6.45 | 3.97 |
| 9 | 17.87 | -0.00 | 0.19 | 1.19 | 0.75 |

Table 7: No Spherical Shoulder, move Z-Axis scenario. SuccessRates

| | Success rate | Valid Region |
|---|---|---|
| Forehand : | 0.58 | [-0.70 0.30] |
| Backhand : | 0.44 | [-0.10 0.50] |

Table 8: Joint Specifcations for No Spherical Shoulder, move Z-Axis scenario. Forehand

| Joint | Max Acc | Min Pos | Max Pos | Max Vel | Max Torque |
|---|---|---|---|---|---|
| 1 | 17.23 | -0.80 | -0.16 | 2.51 | 108.67 |
| 2 | 0.87 | -0.00 | 0.02 | 0.08 | 12.05 |
| 3 | 12.43 | -1.00 | -0.72 | 1.33 | 121.54 |
| 4 | 1.49 | -0.01 | 0.01 | 0.11 | 35.61 |
| 5 | 13.26 | -0.00 | 0.17 | 0.98 | 2.85 |
| 6 | 62.59 | -0.28 | 0.96 | 4.86 | 8.72 |
| 7 | 58.93 | -0.78 | -0.08 | 3.71 | 4.81 |
| 8 | 16.93 | -0.00 | 0.55 | 2.01 | 1.22 |
| 9 | 10.76 | -0.00 | 0.29 | 1.10 | 0.69 |



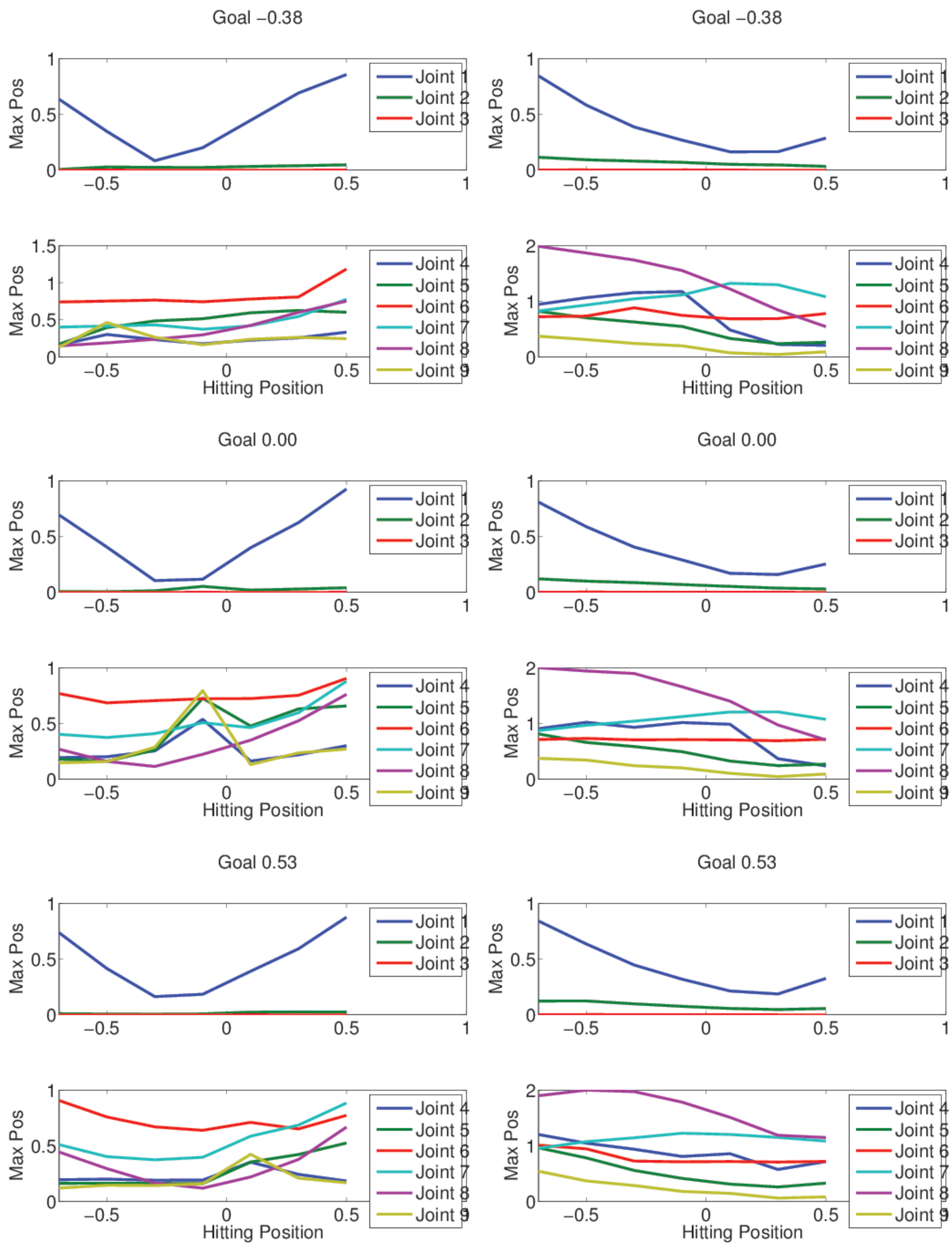

(a) Success

(b) Deviation from target

(c) Success (Backhand)

(d) Deviation from target (Backhand)

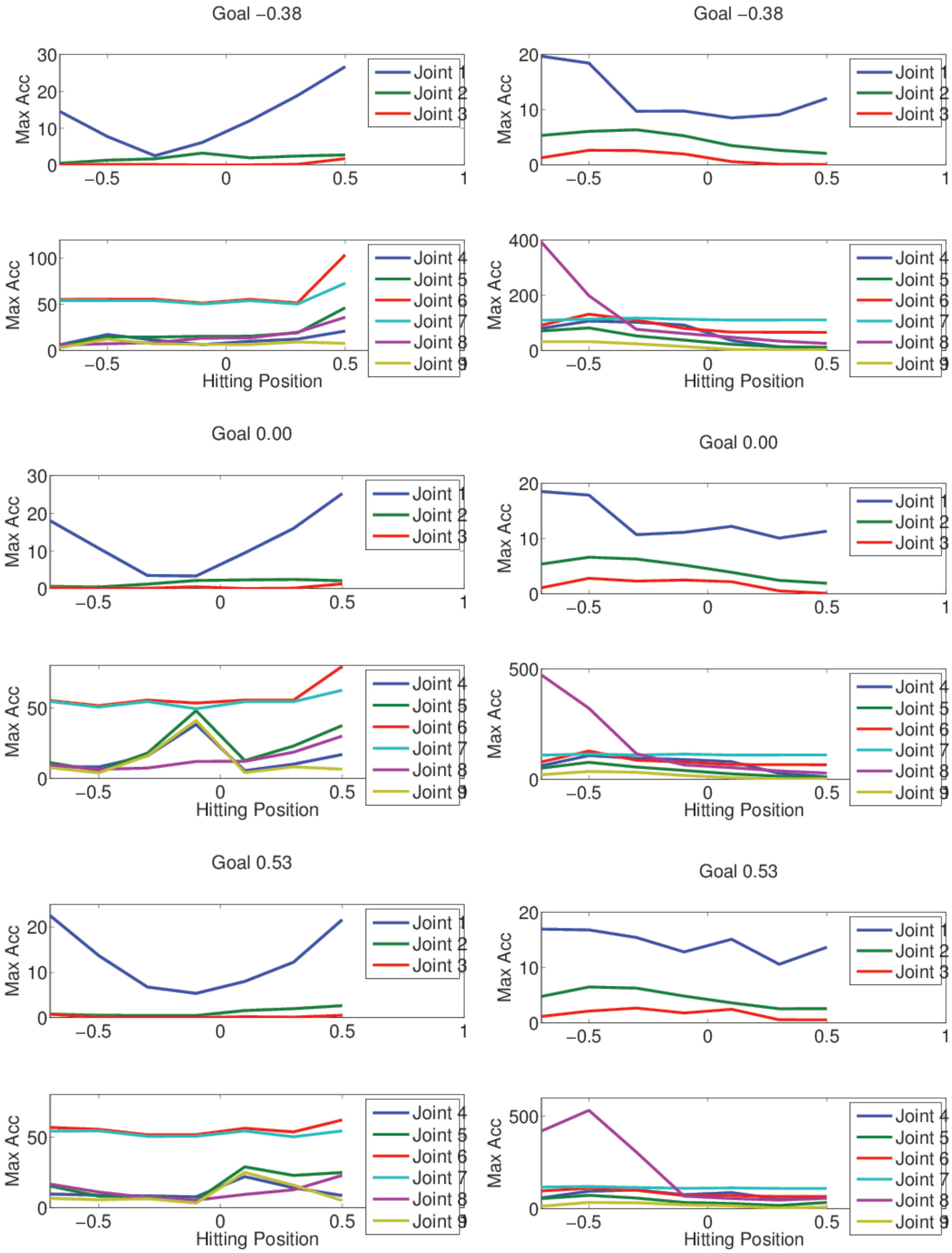
Figure 6: Standard Model : (a) Success rate and (b) deviation from target for 3 different desired targets (point of impact of the ball on the opponents side). The robot needs to hit the ball at different locations. (c-d) same thing for the backhand




(e) ForeHand

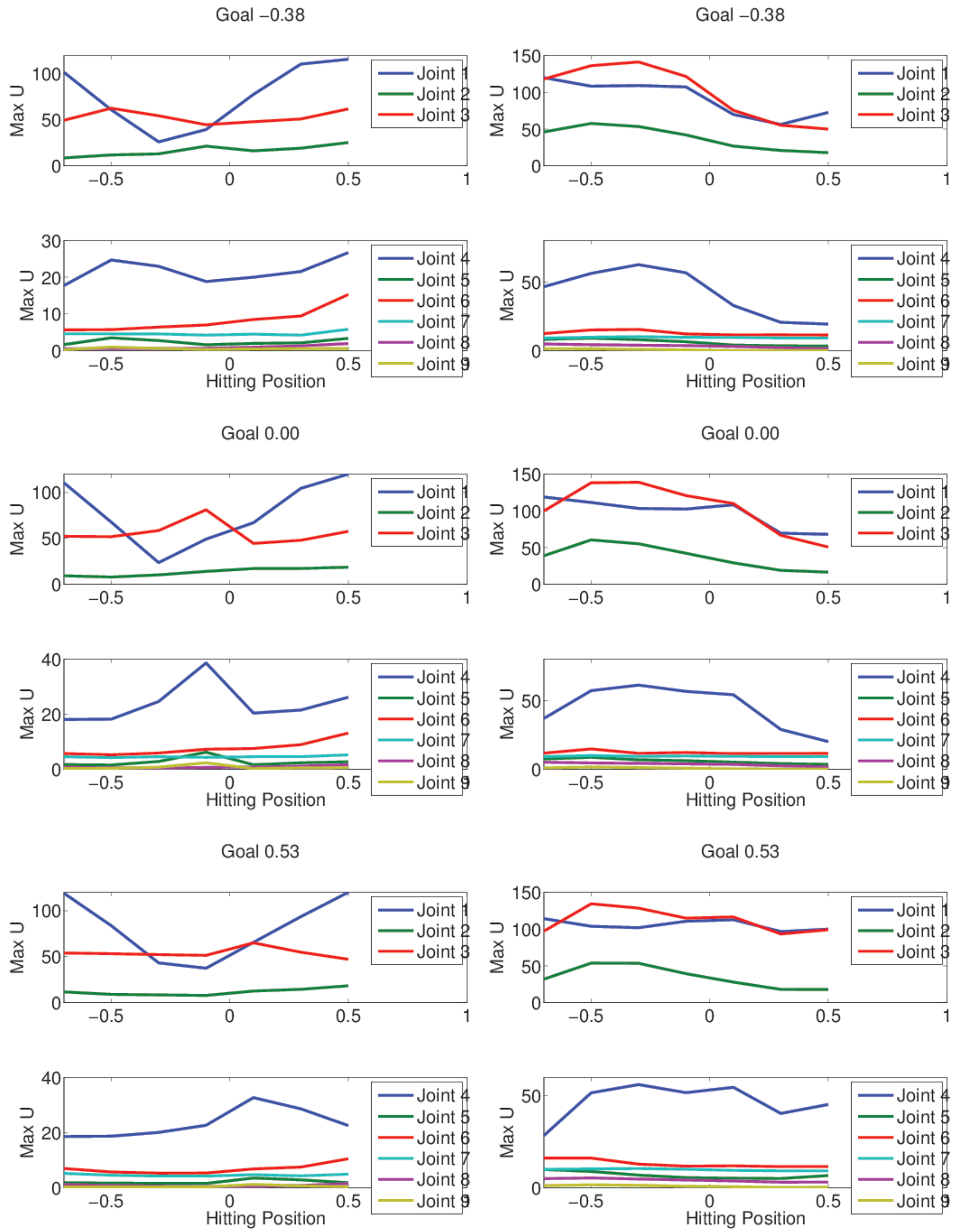
(f) BackHand

Figure 7: Standard Model : Maximum joint deviation from initial position for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand




(e) ForeHand (f) BackHand

Figure 8: Standard Model : Maximum joint acceleration for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand




(e) ForeHand (f) BackHand

Figure 9: Standard Model : Maximum torques for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

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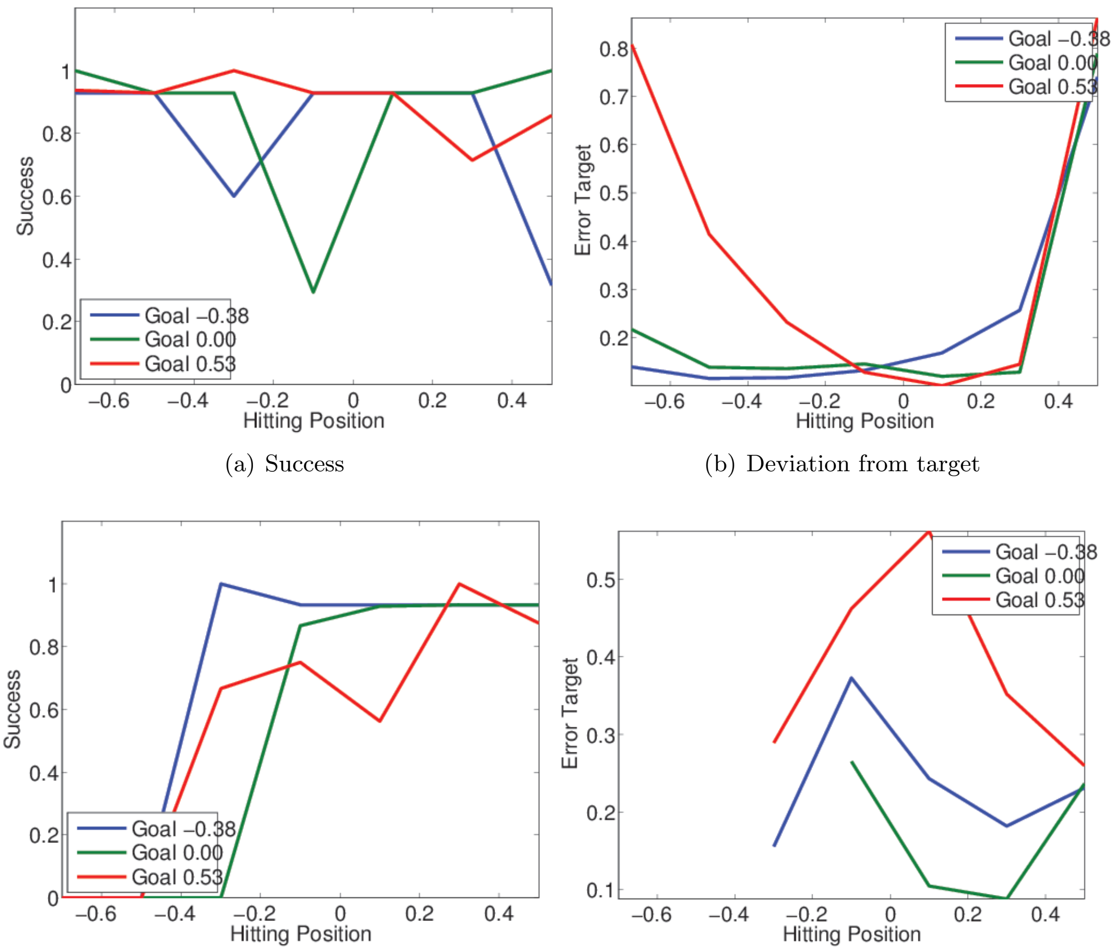


(a) Success

(b) Deviation from target

(c) Success (Backhand)

(d) Deviation from target (Backhand)

Figure 10: No Spherical Shoulder, move Z-Axis : (a) Success rate and (b) deviation from target for 3 different desired targets (point of impact of the ball on the opponents side). The robot needs to hit the ball at different locations. (c-d) same thing for the backhand

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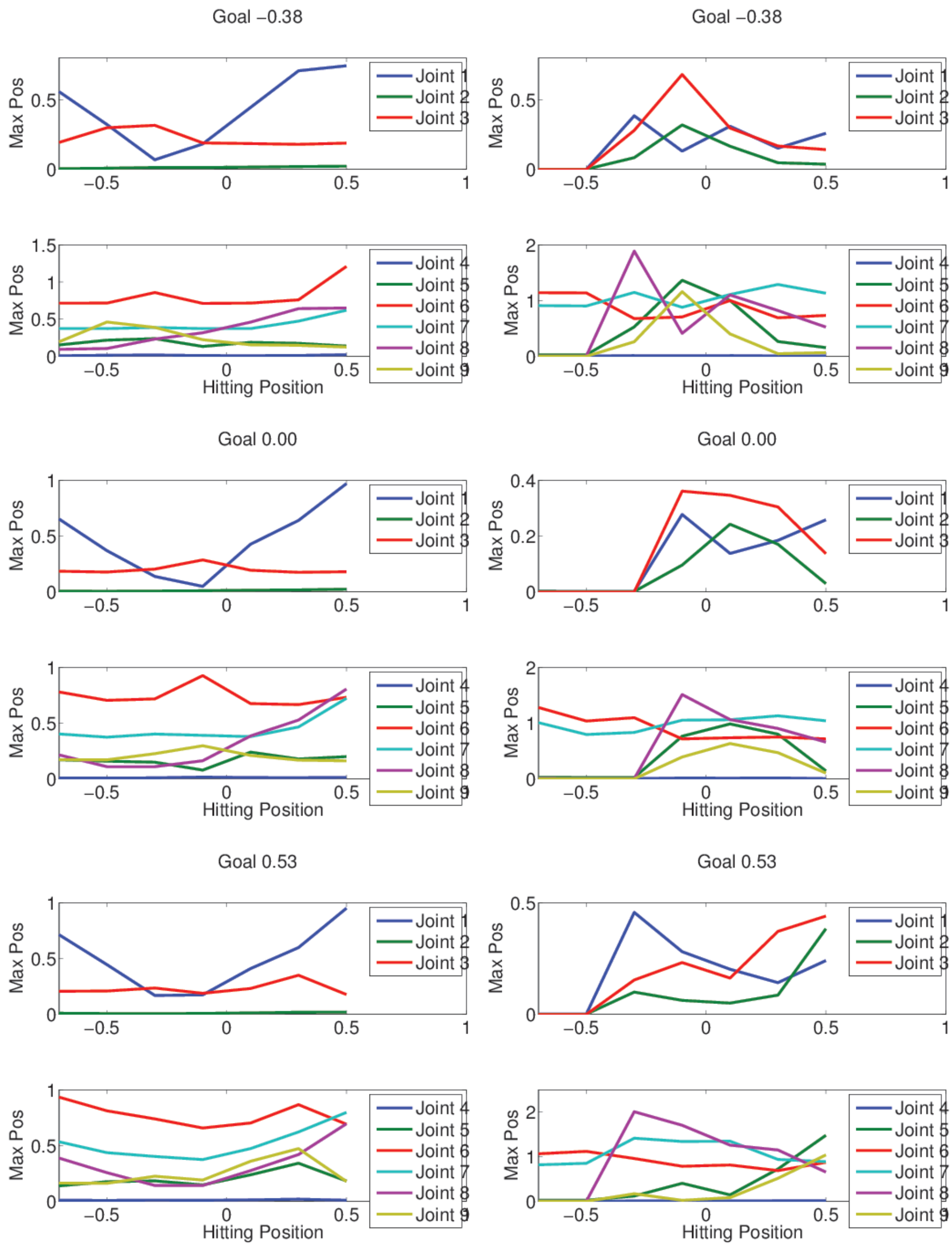


(e) ForeHand (f) BackHand



Figure 11: No Spherical Shoulder, move Z-Axis : Maximum joint deviation from initial position for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

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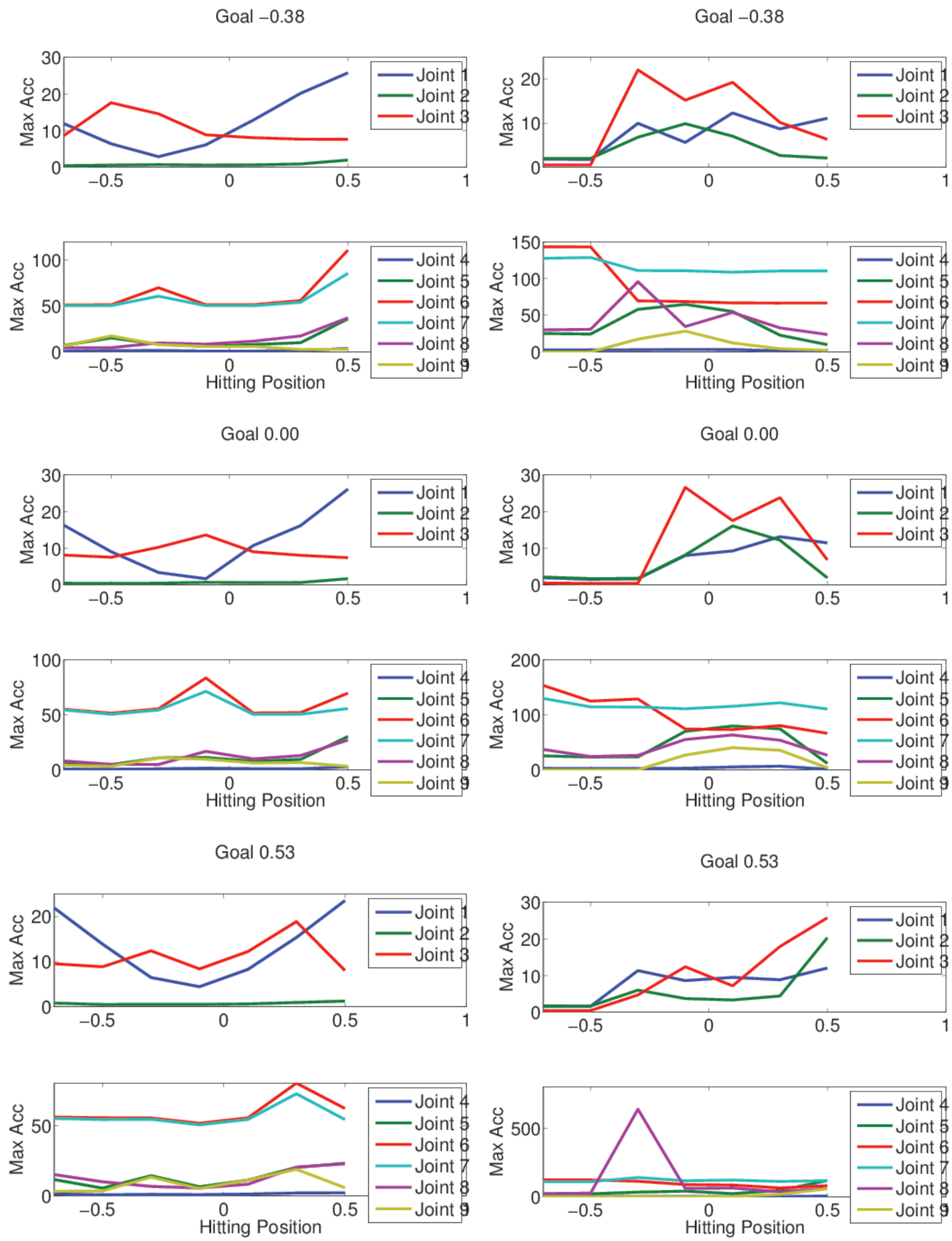


(e) ForeHand (f) BackHand



Figure 12: No Spherical Shoulder, move Z-Axis : Maximum joint acceleration for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

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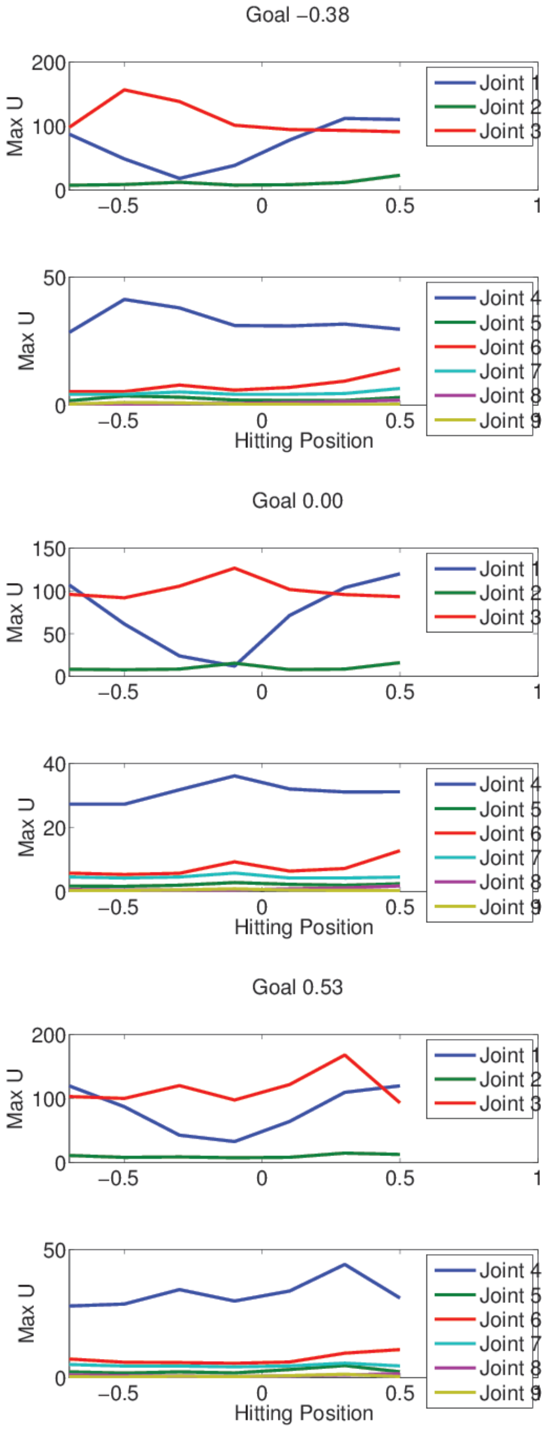
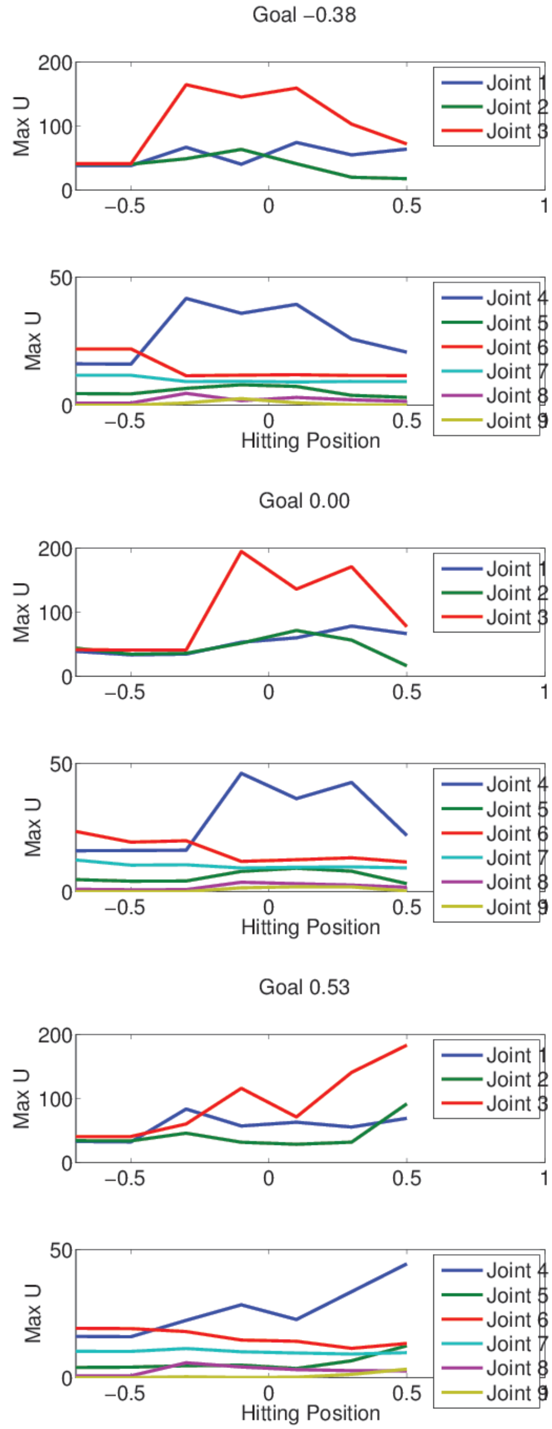



(e) ForeHand




(f) BackHand



Figure 13: No Spherical Shoulder, move Z-Axis : Maximum torques for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

Table 9: Joint Specifcations for No Spherical Shoulder, move Z-Axis scenario. Backhand

| Joint | Max Acc | Min Pos | Max Pos | Max Vel | Max Torque |
|---|---|---|---|---|---|
| 1 | 11.55 | -0.50 | -0.27 | 1.21 | 66.88 |
| 2 | 8.85 | -0.02 | 0.16 | 0.85 | 49.33 |
| 3 | 18.08 | -0.91 | -0.40 | 2.12 | 152.16 |
| 4 | 3.52 | -0.01 | 0.01 | 0.16 | 36.76 |
| 5 | 58.86 | -0.05 | 0.71 | 4.54 | 6.92 |
| 6 | 77.48 | -1.44 | -0.22 | 5.04 | 12.84 |
| 7 | 115.41 | -1.41 | 0.06 | 7.59 | 9.53 |
| 8 | 60.65 | -0.61 | 0.07 | 5.09 | 3.21 |
| 9 | 21.93 | -0.06 | 0.35 | 2.18 | 1.37 |

# 5 No Spherical Shoulder, No Z-Axis

In this model we disabled the linear axis for the Z-direction (up/down). The evaluations can be seen in Figure 14 to 17 for the forehand hitting movement and backhand hitting movement.

# 6 No Z-Axis, Disabled last wrist joint

In this model we disabled the linear axis for the Z-direction (up/down). The evaluations can be seen in Figure 18 to 21 for the forehand hitting movement and backhand hitting movement.

# 7 Conclusion

The standard model seems to be most robust, showing the best success rate of hitting the ball and also the smallest deviation from error. However, the standard model uses the additional shoulder joint which might be difficult to build. The standard model can return almost all balls from the whole hitting range while the maximum accelerations for the linear axis is less than $20s^{-2}$. Also the backhand hitting movement could return all balls but with considerably higher deviation from the desired target.

Disabling the shoulder joint, but enabling the linear Z-axis already decreases the performance a little bit, but it seems still to work quite well. However, using an rotational joint instead of the Z-axis would from the bio-mimetic point of view be much more appealing. If the shoulder joint and the z-axis are disabled almost all accuracy for aiming is gone as the robot is not able to set the height of the hitting point any more.

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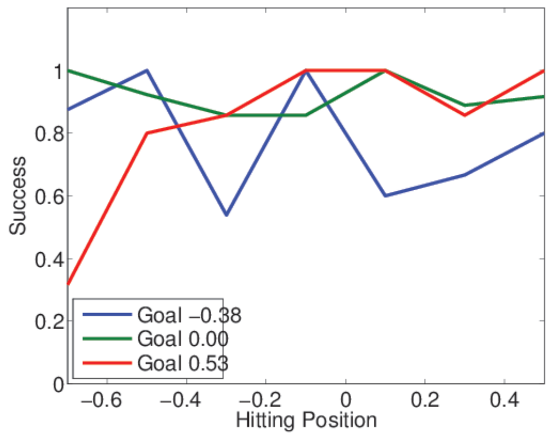
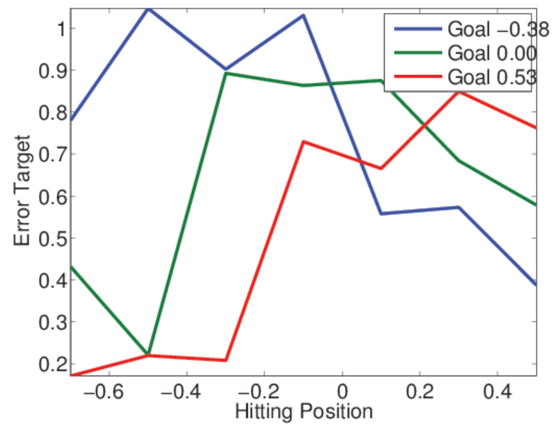
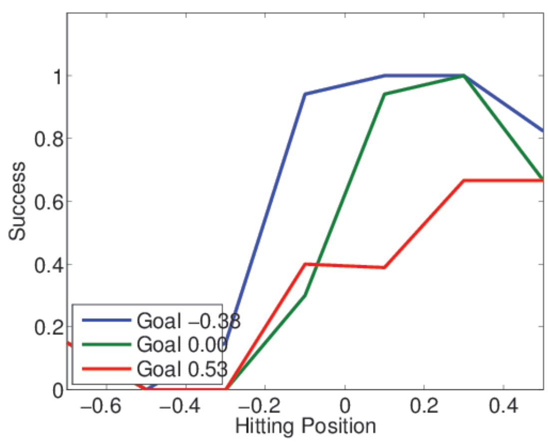


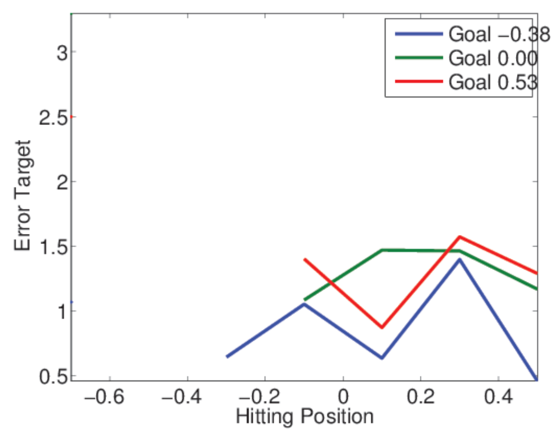

(a) Success




(b) Deviation from target




(c) Success (Backhand)




(d) Deviation from target (Backhand)

Figure 14: No Spherical Shoulder, no Z-Axis : (a) Success rate and (b) deviation from target for 3 different desired targets (point of impact of the ball on the opponents side). The robot needs to hit the ball at different locations. (c-d) same thing for the backhand

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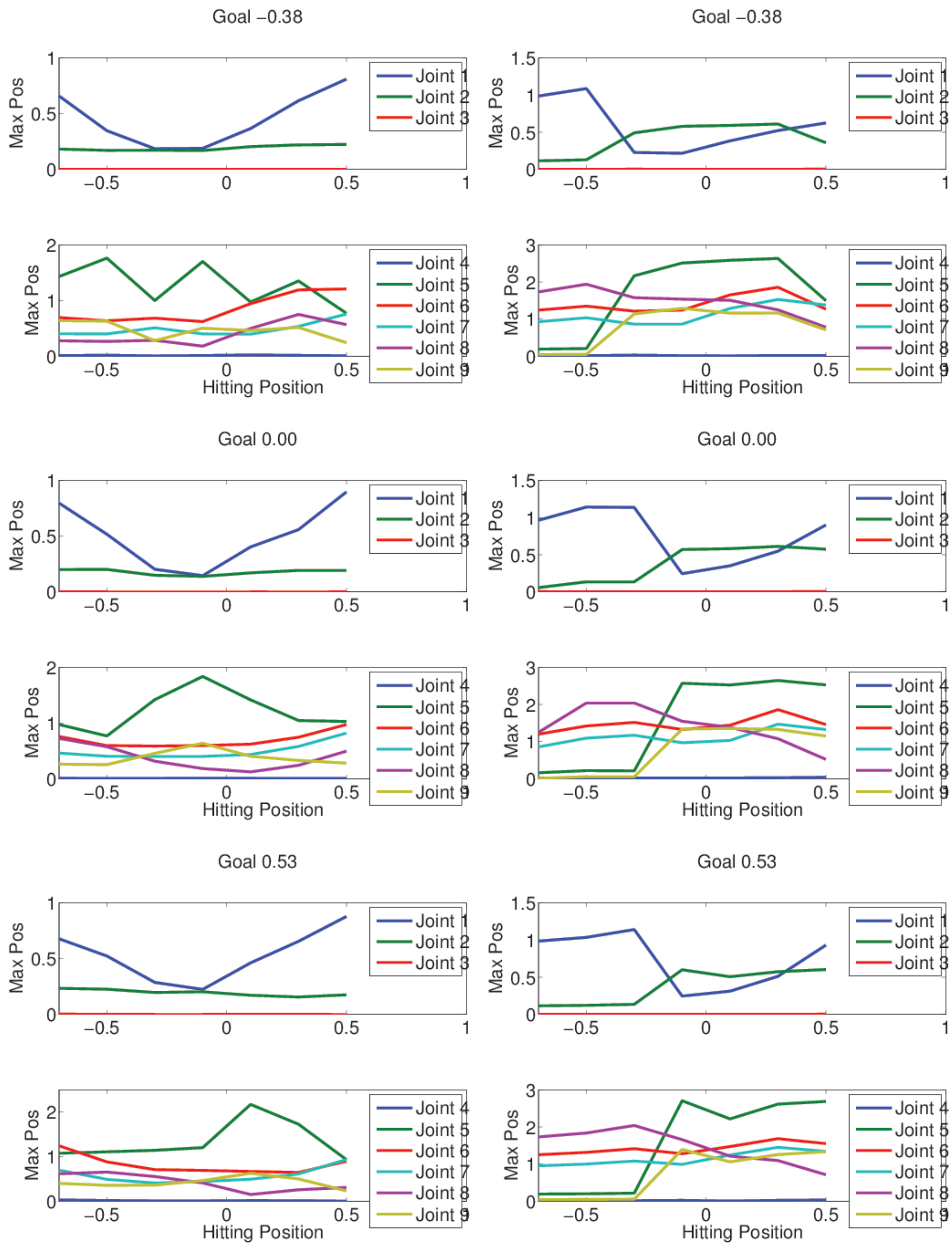


(e) ForeHand (f) BackHand



Figure 15: No Spherical Shoulder, no Z-Axis : Maximum joint deviation from initial position for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

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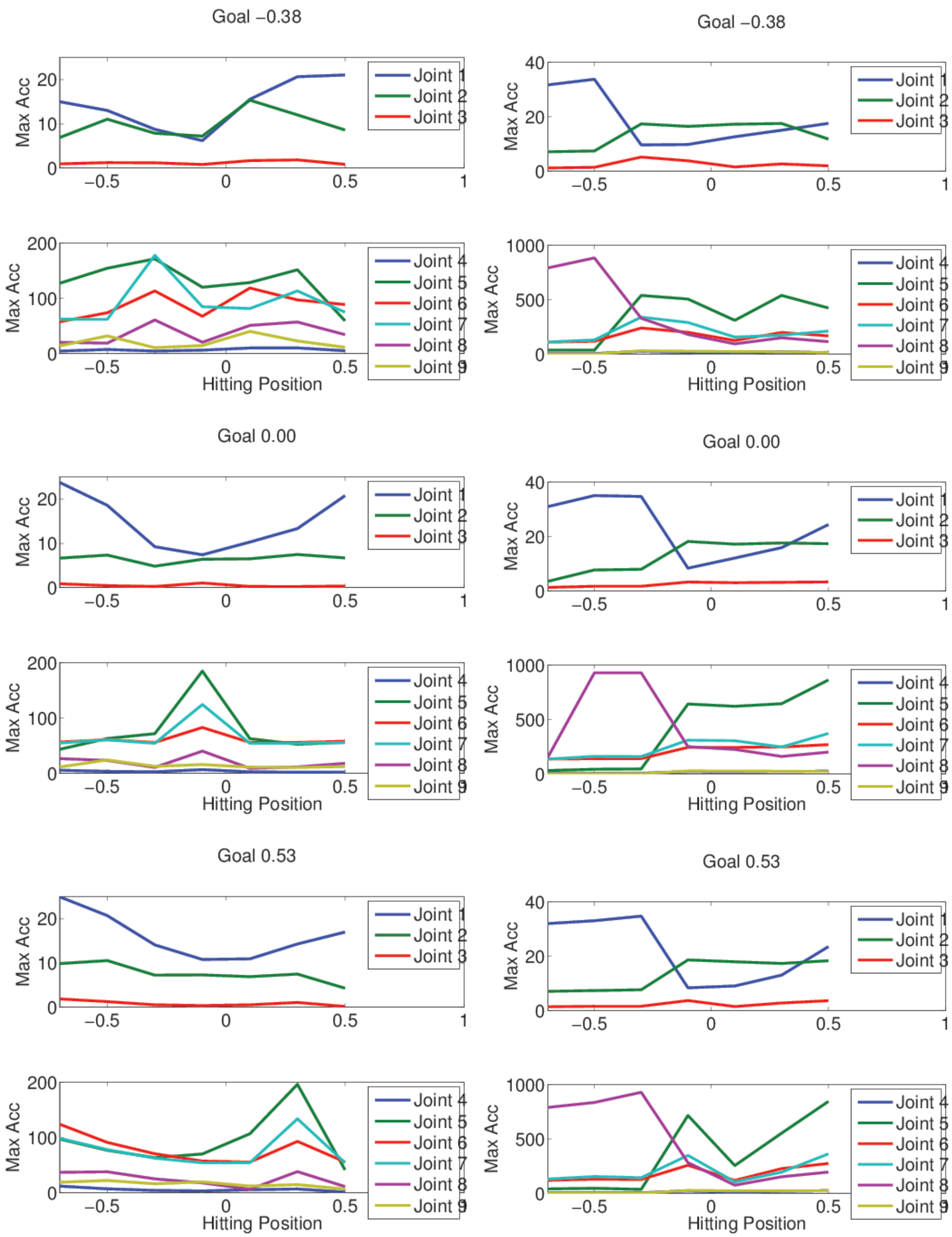


(e) ForeHand (f) BackHand

Figure 16: No Spherical Shoulder, no Z-Axis : Maximum joint acceleration for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

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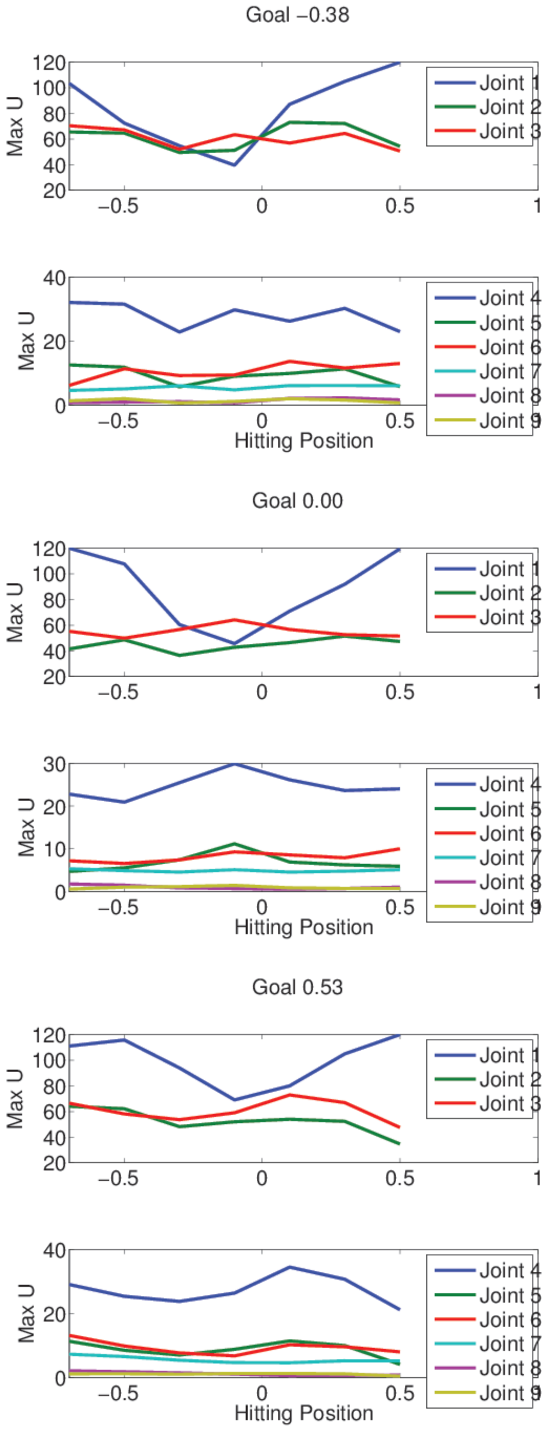
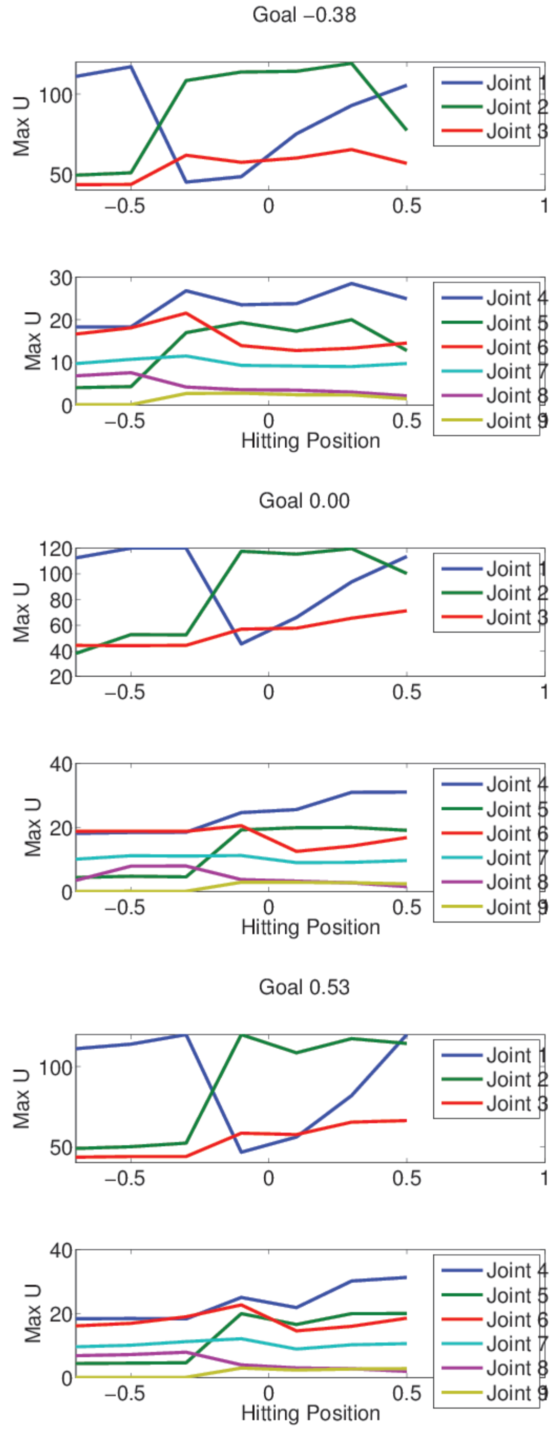



(e) ForeHand




(f) BackHand

Figure 17: No Spherical Shoulder, no Z-Axis : Maximum torques for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

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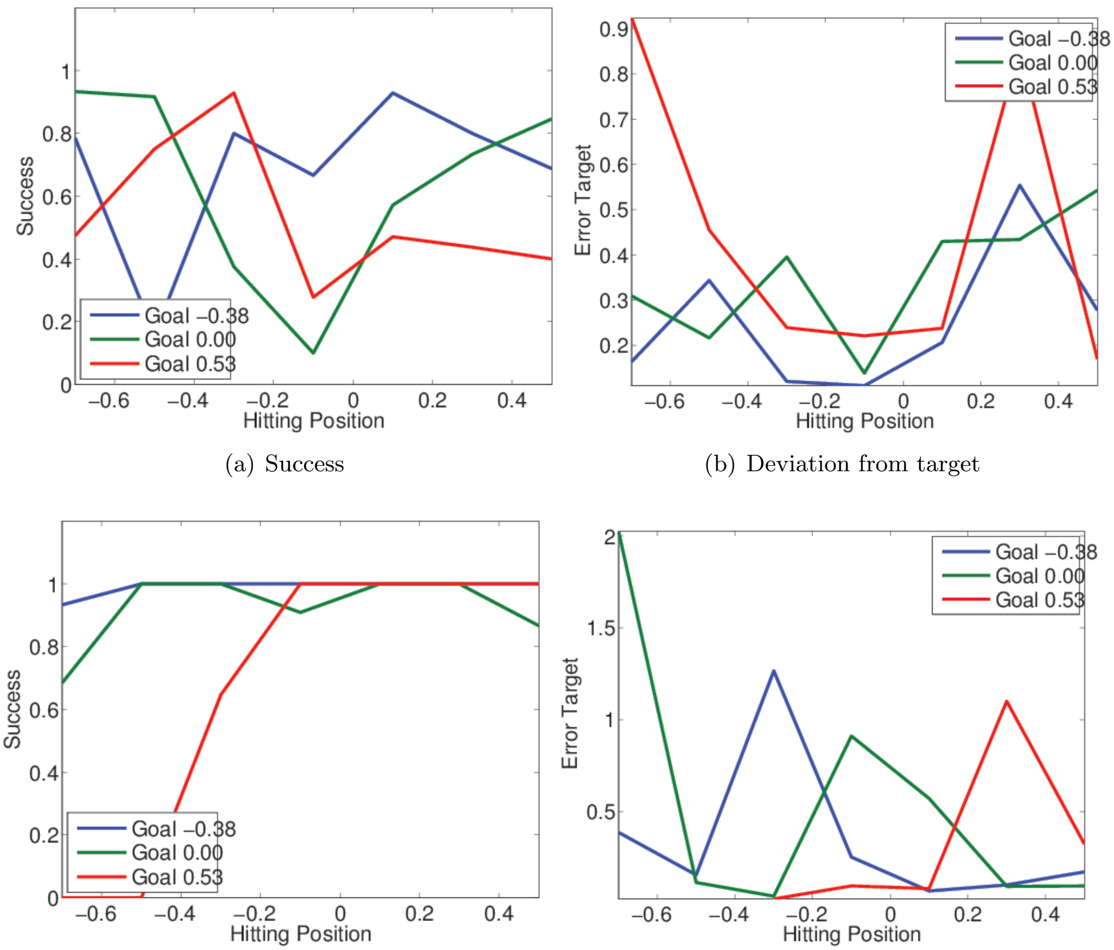


(a) Success

(b) Deviation from target

(c) Success (Backhand)

(d) Deviation from target (Backhand)

Figure 18: No last joint : (a) Success rate and (b) deviation from target for 3 different desired targets (point of impact of the ball on the opponents side). The robot needs to hit the ball at different locations. (c-d) same thing for the backhand

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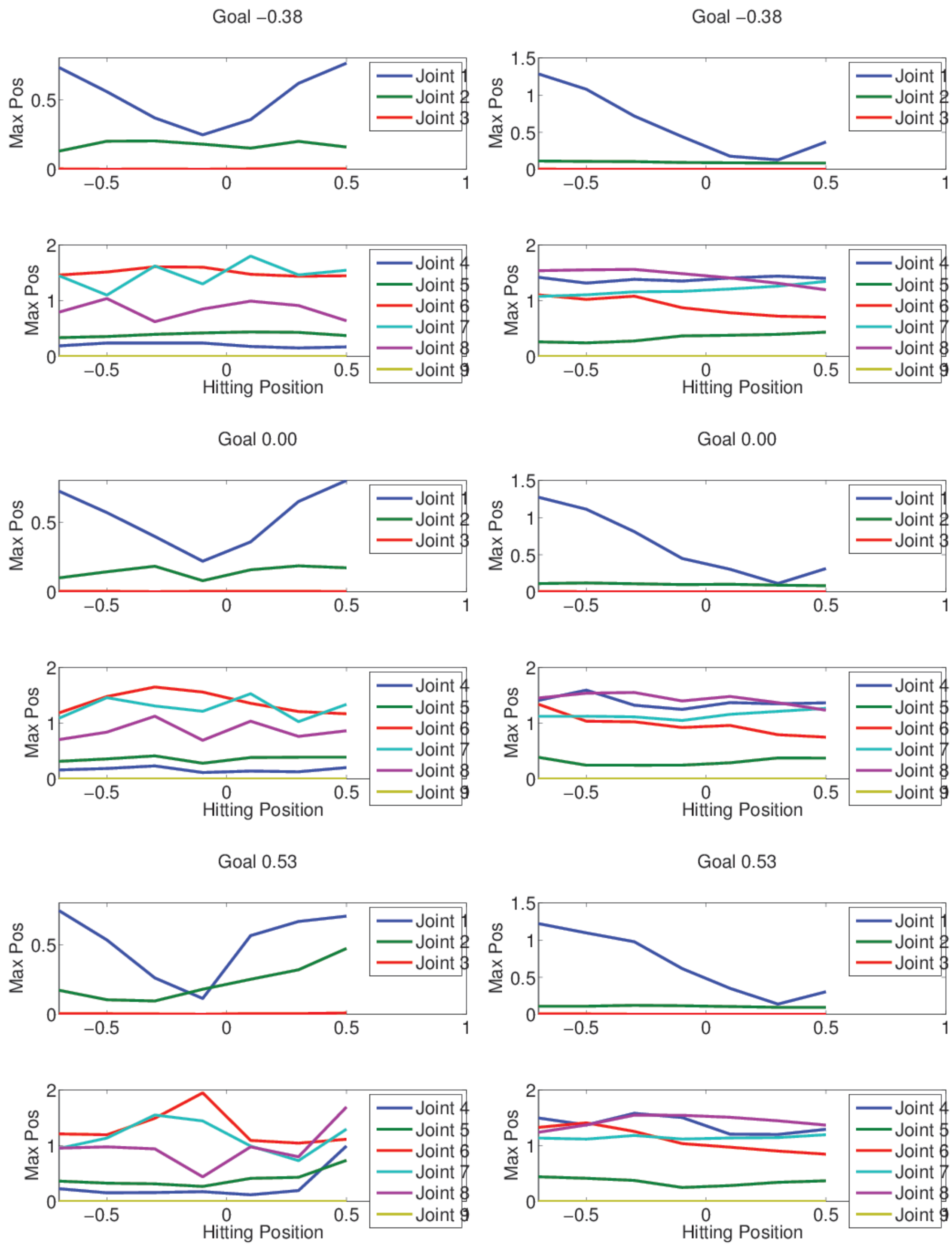


(e) ForeHand (f) BackHand



Figure 19: No last joint : Maximum joint deviation from initial position for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

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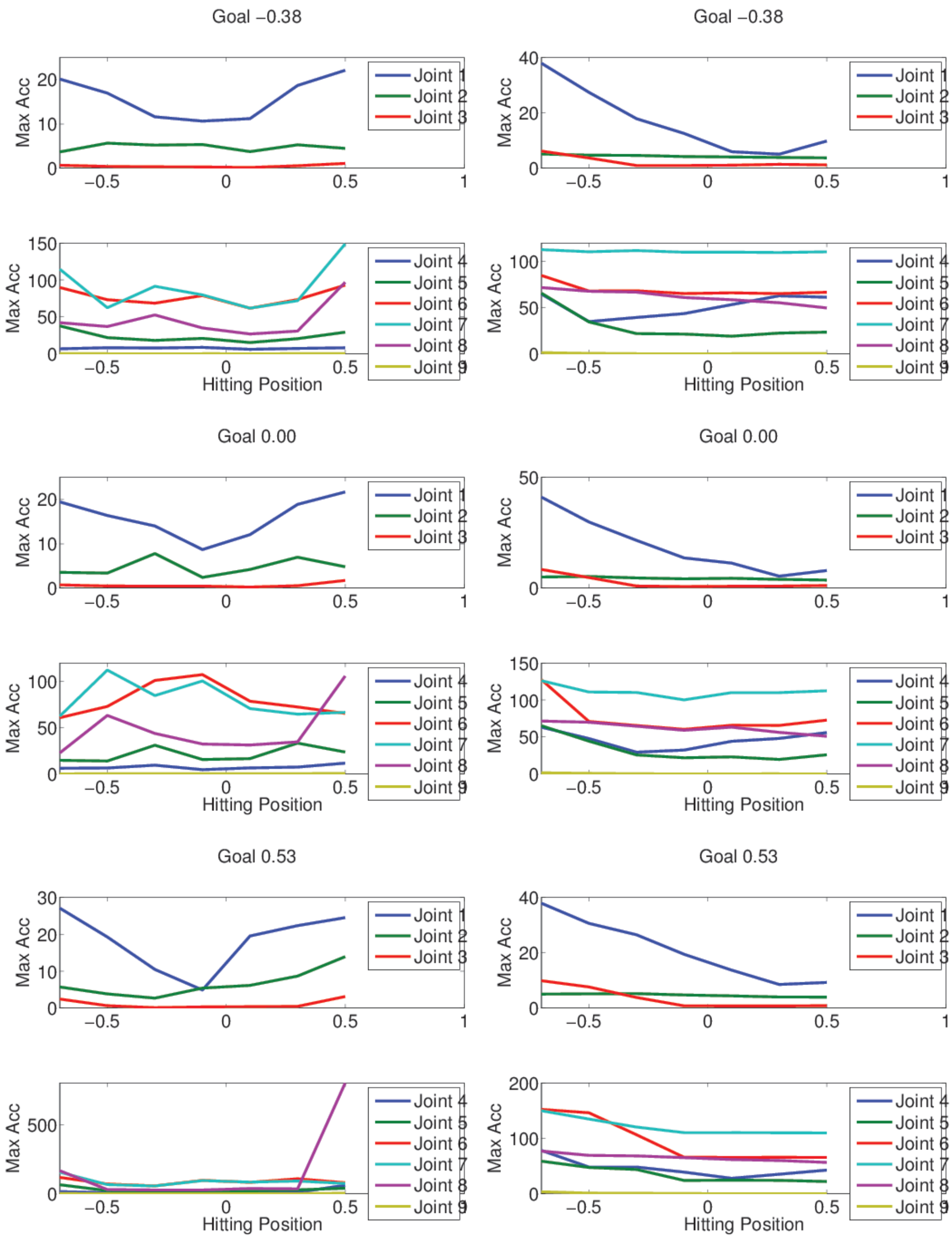


(e) ForeHand

(f) BackHand

Figure 20: No last joint : Maximum joint acceleration for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

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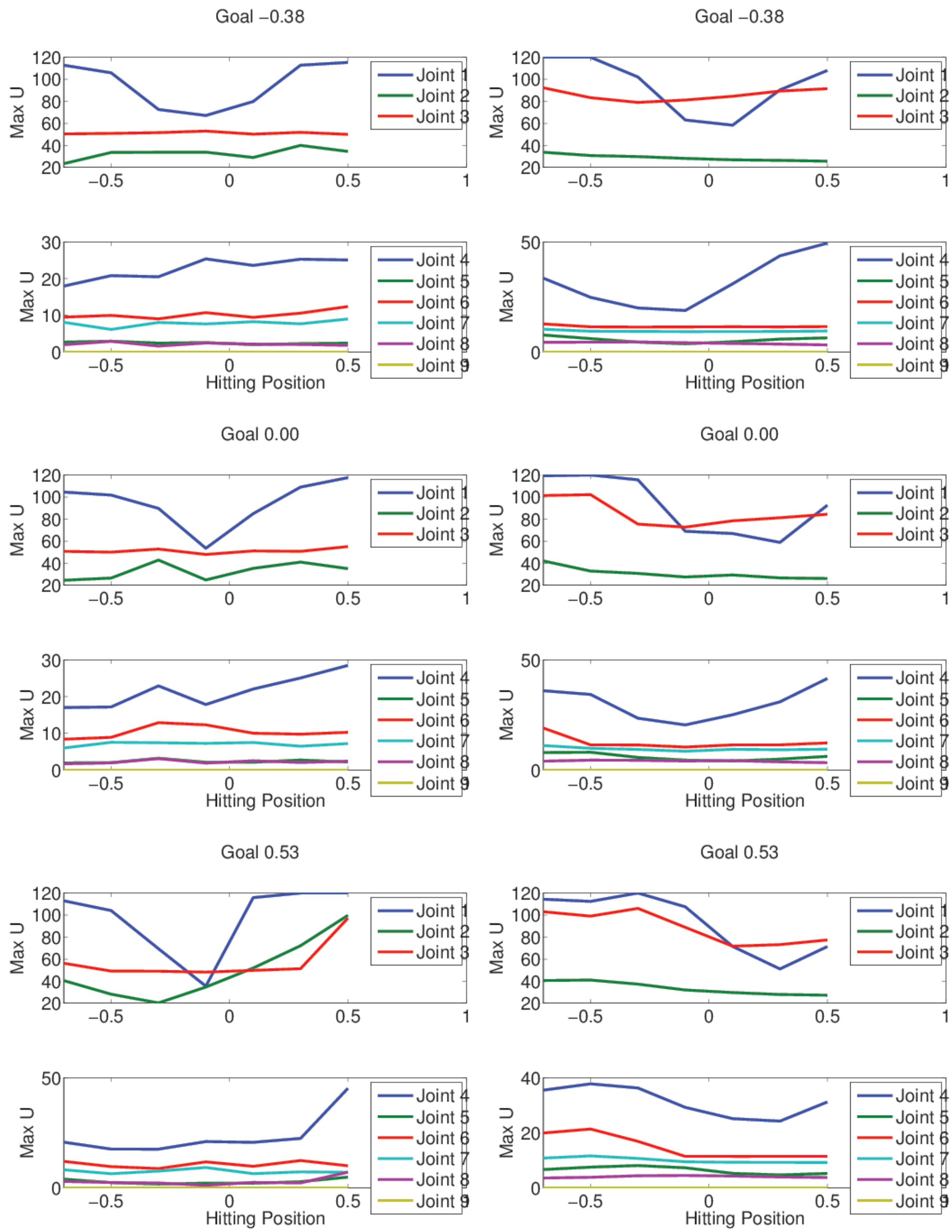


(e) ForeHand

(f) BackHand



Figure 21: No last joint : Maximum torques for different hitting points, 1st target. (a,c,e) forehand, (b,d,f) backhand

In the last experiment we disabled the last joint at the wrist. Unfortunately the performance also decreased considerably in this setup, forehand play seems to rely on this joint.