1 IROS 2022 Experiment Description

1.1 Performance Metrics

In order to evaluate the relative performance of the reflexes with respect to safety we use the following metrics. The first two are stemming from [1] and ISO/TS 15066, our reasons for choosing the others will be elaborated in the following.

1. Maximum contact force $J_\mathrm{f} = \max_{t=0}^{t_\mathrm{end}} ||\boldsymbol{f}_\mathrm{ext}(t)||$
2. Mean static force 0.5 s after start of the contact $J_\mathrm{s} = 1/t_\mathrm{end} \int_{t=0.5}^{t_\mathrm{end}} ||\boldsymbol{f}_\mathrm{ext}||\, dt$
3. Mean static force 0.05 s after start of the contact $J_\mathrm{s} = 1/t_\mathrm{end} \int_{t=0.05}^{t_\mathrm{end}} ||\boldsymbol{f}_\mathrm{ext}||\, dt$
4. Energy exchange $J_\mathrm{e} = \int_{t=0}^{t_\mathrm{end}} |\boldsymbol{\mathcal{F}}_\mathrm{ext}^\mathrm{T} \dot{\boldsymbol{x}}_\mathrm{c}|\, dt$
5. Contact duration $J_\mathrm{t} = t_\mathrm{end}$
6. Change in momentum $J_{\alpha_\beta} = \int_{t=0}^{t_\mathrm{end}} |\alpha_\beta| dt, \quad \alpha \in \{\boldsymbol{f}, \boldsymbol{m}\}, \quad \beta \in \{x, y, z\}$ (evaluated for f_x only, no significant forces/torques in the other options)
7. Maximum distance traveled from desired position at time of contact recognition after reflex $J_\mathrm{d} = \max ||\boldsymbol{p}(t_0) - \boldsymbol{p}(t_\mathrm{end})||$
8. Maximum velocity after contact $J_\mathrm{v} = \max_{t>t_\mathrm{end}} ||\dot{\boldsymbol{p}}(t)||$

Above t_0 and t_end denote the time where the contact that triggers the reflex starts and ends, respectively. The external wrench $\boldsymbol{\mathcal{F}}_\mathrm{ext} = \begin{pmatrix} \boldsymbol{f}_\mathrm{ext}^\mathrm{T} & \boldsymbol{m}_\mathrm{ext}^\mathrm{T} \end{pmatrix}^\mathrm{T}$ is the combination of the vector of external force $\boldsymbol{f}_\mathrm{ext}$ and the vector of external Cartesian torque $\boldsymbol{m}_\mathrm{ext}$. The vector $\dot{\boldsymbol{x}}_\mathrm{c}$ denotes the twist of the contact point while $\boldsymbol{p}(t)$ denotes the position of the robots' end-effector over time.

During the experiments, we observed that for all strategies but the ones that include stop in the name (see section 1.2), the contact is generally over after 250 ms latest. We therefore included criterion three in order to investigate robot's behaviour after the first impact. The idea behind the fourth criterion is that the energy exchanged between the robot and the environment limits the energy available for deformation of the collided object. As short contact is often more desirable, we also devised criterion five. It could lead to dangerous situations, if the collided entity has a high speed after the collision, which inspired criterion six. The farther we move away from the contact location during the reflex, the higher will the risk of hitting something else be, which inspired criterion seven. Being close to the contact location after the reflex will furthermore make it easier to recover the task successfully. For all criteria a low value is desirable. Furthermore, reflexes have to take into account the object in hand and choose compatible reactions. The last point was not be evaluated in this experiment due to the high number of different possible objects and limitations of the measurement system.

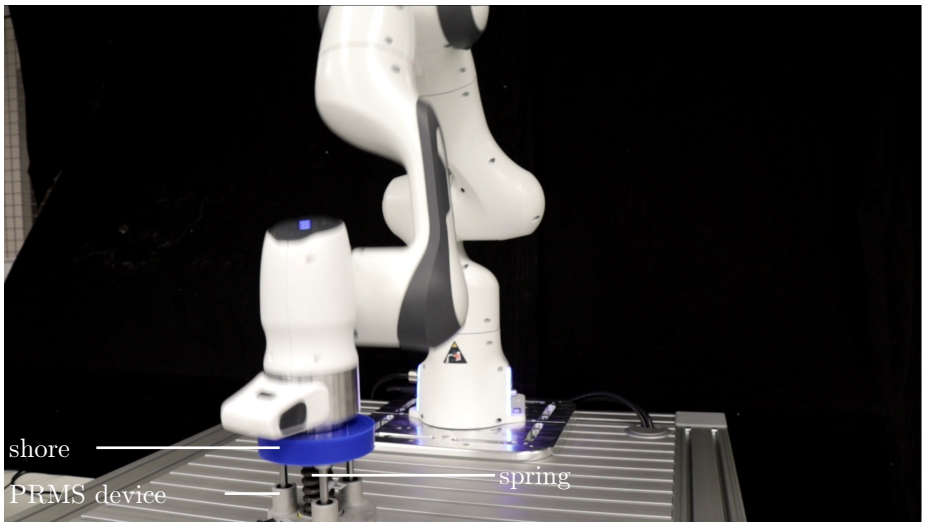

Figure 1: Panda Robot colliding with the PRMS device to evaluate the performance metrics. The blue shore A 30 together with the 60 N/mm spring simulates the collision behavior of the calf muscle.

1.2 Performance Evaluation for Reflex Maneuvers

In order to evaluate the relative performance of our reflex maneuvers, we first measured the performance metrics for the primitives reflexes in our previous work [2] – also including novel ones – using the collision pressure measuring kit PRMS by company Pilz, to obtain force curves and peak impact forces as well as the internal robot data. The reflexes from our previous work are changing the control to either admittance control, zero-g, super-zero-g (zero-g control with inertia shaping) or stop the robot by fixing the current control goal at the position of contact detection. We furthermore considered active retractions in joint and Cartesian space using a joint and Cartesian impedance controller respectively. For the retraction reflexes, the desired position is set to be 5 cm (joint) or 9 cm (Cartesian) away from the point of contact detection into the direction of the external joint torque or Cartesian force respectively.

Based on the results, we designed the following three reflex maneuvers that were evaluated as well: "admittance-stop", where we switch to admittance control until we detect that we are more than 2 cm away from the contact location, "super-stop", where the same is done with super-zero-g instead of admittance and "stop-retract" where the robot first stops and then retracts after 100 ms using the joint retraction reflex with the highest external torques that were measured in between. It is worth highlighting that, to the best of author's knowledge, this is the most complete experimental study analysis in terms of number of reflex strategies and compliant controllers often deployed for pHRI. It is also the first study of this kind to integrate switched controllers for safety-assessment.

All of the above strategies are evaluated by having them collide with a predefined trajectory at velocities of 0.04, 0.08, 0.15 and 0.25 m/s with the PRMS device configured to model the behavior of the three body parts adbominal muscle (soft), calf muscle (medium) and upper forehead (hard), see Fig. 1. The contact thresholds were defined as 10 N absolute external Cartesian force and 3 Nm absolute external Cartesian torques as well as external joint torques of $\begin{pmatrix} 4 & 4 & 3 & 3 & 1 & 1 & 0.5 \end{pmatrix}$ Nm respectively. The mean and variance over ten trials for each of the twelve experiments per strategy were calculated. The results are shown in the following tables.

2 criterion 1

2.1 Evaluated with data from PRMS device

Table 1: criterion 1 measured by PRMS device for collisions at velocity 0.04 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.623e+01	1.418e+01	1.171e+01	4.500e−01	4.549e−01	7.885e−02
admittance-stop	1.965e+01	1.651e+01	1.179e+01	6.721e−01	2.439e−01	2.501e−01
cart-retraction	1.610e+01	1.464e+01	1.188e+01	3.269e−01	4.114e−01	3.003e−01
joint-retraction	1.776e+01	1.502e+01	1.150e+01	7.294e−01	2.301e−01	3.228e−01
stop	1.801e+01	1.518e+01	1.185e+01	5.548e−01	3.139e−01	1.773e−01
stop-retract	1.921e+01	1.652e+01	1.235e+01	8.339e−01	4.706e−01	2.949e−01
super-stop	1.856e+01	1.578e+01	1.184e+01	5.878e−01	4.835e−01	2.949e−01
super-zero-g	1.549e+01	1.523e+01	1.095e+01	4.023e−01	5.981e−01	1.764e−01
zero-g	1.976e+01	1.558e+01	1.175e+01	3.569e−01	2.569e−01	2.603e−01

Table 2: criterion 1 measured by PRMS device for collisions at velocity 0.08 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	4.424e+01	2.943e+01	2.109e+01	1.105e+00	5.474e−01	2.873e−01
admittance-stop	4.671e+01	3.174e+01	2.330e+01	6.197e−01	3.879e−01	3.408e−01
cart-retraction	4.591e+01	2.959e+01	2.241e+01	4.991e−01	3.387e−01	2.828e−01
joint-retraction	4.708e+01	3.074e+01	2.274e+01	4.851e−01	5.883e−01	2.899e−01
stop	4.405e+01	2.725e+01	1.836e+01	9.242e−01	6.417e−01	2.515e−01
stop-retract	3.951e+01	3.296e+01	2.406e+01	1.836e+00	4.213e−01	1.514e−01
super-stop	4.304e+01	3.147e+01	2.322e+01	6.891e−01	2.846e−01	2.979e−01
super-zero-g	4.648e+01	2.979e+01	2.166e+01	1.288e+00	3.820e−01	4.096e−01
zero-g	4.594e+01	2.898e+01	2.169e+01	1.572e+00	4.536e−01	2.910e−01

Table 3: criterion 1 measured by PRMS device for collisions at velocity 0.15 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	9.730e+01	6.432e+01	4.023e+01	1.365e+00	1.345e+00	8.332e−01
admittance-stop	7.888e+01	6.783e+01	4.217e+01	1.223e+00	4.712e−01	3.077e−01
cart-retraction	9.511e+01	6.389e+01	3.947e+01	9.320e−01	5.534e−01	3.823e−01
joint-retraction	9.658e+01	6.495e+01	3.966e+01	1.410e+00	1.014e+00	2.605e−01
stop	9.578e+01	6.051e+01	3.107e+01	3.667e+00	2.130e+00	2.201e−01
stop-retract	7.576e+01	6.816e+01	4.178e+01	1.114e+00	3.599e−01	3.391e−01
super-stop	7.422e+01	6.791e+01	4.122e+01	2.138e+00	4.189e−01	3.425e−01
super-zero-g	8.856e+01	6.433e+01	3.942e+01	1.021e+00	2.948e−01	1.284e−01
zero-g	9.238e+01	6.432e+01	4.007e+01	1.073e+00	5.244e−01	2.561e−01

Table 4: criterion 1 measured by PRMS device for collisions at velocity 0.25 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.421e+02	1.208e+02	6.693e+01	5.469e+00	5.689e−01	5.691e+00
admittance-stop	1.449e+02	1.194e+02	6.919e+01	1.606e+00	1.272e+00	1.211e+00
cart-retraction	1.433e+02	1.182e+02	6.469e+01	1.125e+00	1.108e+00	6.896e−01
joint-retraction	1.477e+02	1.192e+02	6.593e+01	1.876e+00	8.338e−01	3.013e−01
stop	1.501e+02	1.205e+02	6.680e+01	2.261e+00	8.914e−01	8.723e−01
stop-retract	1.393e+02	1.206e+02	6.731e+01	3.533e+00	7.507e−01	1.520e+00
super-stop	1.432e+02	1.183e+02	6.412e+01	2.419e+00	6.814e−01	5.843e−01
super-zero-g	1.498e+02	1.207e+02	6.492e+01	3.053e+00	1.002e+00	3.434e−01
zero-g	1.443e+02	1.197e+02	6.563e+01	3.794e+00	8.480e−01	4.035e−01

2.2 Evaluated with data from robot

Table 5: criterion 1 measured by robot for collisions at velocity 0.04 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.331e+01	1.229e+01	1.142e+01	2.399e−01	1.450e−01	1.240e−01
admittance-stop	1.339e+01	1.313e+01	1.191e+01	2.290e−01	2.082e−01	1.968e−01
cart-retraction	1.386e+01	1.326e+01	1.311e+01	1.729e−01	2.399e−01	3.870e−01
joint-retraction	1.405e+01	1.319e+01	1.247e+01	3.457e−01	1.111e−01	3.927e−01
stop	1.287e+01	1.210e+01	1.105e+01	2.515e−01	1.854e−01	1.295e−01
stop-retract	1.214e+01	1.250e+01	1.159e+01	3.085e−01	2.524e−01	2.643e−01
super-stop	1.284e+01	1.325e+01	1.252e+01	2.970e−01	1.736e−01	2.442e−01
super-zero-g	1.428e+01	1.260e+01	1.177e+01	1.490e−01	1.759e−01	2.313e−01
zero-g	1.300e+01	1.211e+01	1.114e+01	1.490e−01	1.738e−01	1.965e−01

Table 6: criterion 1 measured by robot for collisions at velocity 0.08 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	2.725e+01	2.134e+01	1.566e+01	3.914e−01	1.371e−01	2.047e−01
admittance-stop	2.458e+01	2.255e+01	1.683e+01	2.121e−01	1.778e−01	2.922e−01
cart-retraction	2.802e+01	2.216e+01	1.733e+01	1.908e−01	1.620e−01	2.931e−01
joint-retraction	2.807e+01	2.129e+01	1.784e+01	2.257e−01	1.453e−01	4.135e−01
stop	2.606e+01	2.029e+01	1.842e+01	2.867e−01	2.947e−01	1.836e−01
stop-retract	2.197e+01	2.122e+01	1.919e+01	4.735e−01	8.022e−02	1.237e−01
super-stop	2.462e+01	2.259e+01	1.753e+01	3.034e−01	2.263e−01	1.773e−01
super-zero-g	2.801e+01	2.160e+01	1.615e+01	3.059e−01	4.017e−01	2.626e−01
zero-g	2.668e+01	2.057e+01	1.739e+01	5.874e−01	1.632e−01	2.202e−01

Table 7: criterion 1 measured by robot for collisions at velocity 0.15 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	5.242e+01	4.033e+01	2.589e+01	4.092e−01	5.553e−01	4.527e−01
admittance-stop	4.772e+01	4.147e+01	2.718e+01	7.647e−01	4.049e−01	3.262e−01
cart-retraction	5.175e+01	3.983e+01	2.640e+01	4.162e−01	2.858e−01	3.265e−01
joint-retraction	5.162e+01	3.968e+01	2.614e+01	3.455e−01	6.208e−01	2.230e−01
stop	4.852e+01	3.805e+01	3.214e+01	7.638e−01	4.140e−01	2.630e−01
stop-retract	4.341e+01	3.879e+01	3.441e+01	3.461e−01	2.525e−01	3.080e−01
super-stop	4.652e+01	4.103e+01	2.857e+01	3.898e−01	3.804e−01	3.102e−01
super-zero-g	5.149e+01	3.998e+01	2.679e+01	5.370e−01	4.601e−01	1.958e−01
zero-g	5.058e+01	3.845e+01	2.970e+01	1.743e−01	2.726e−01	1.918e−01

Table 8: criterion 1 measured by robot for collisions at velocity 0.25 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	7.401e+01	7.017e+01	4.384e+01	1.076e+00	4.780e−01	4.726e+00
admittance-stop	7.745e+01	6.912e+01	4.460e+01	3.999e−01	4.117e−01	5.955e−01
cart-retraction	7.319e+01	6.740e+01	4.592e+01	4.310e−01	7.045e−01	4.996e−01
joint-retraction	7.418e+01	6.715e+01	4.218e+01	1.396e+00	4.656e−01	6.249e−01
stop	7.123e+01	6.518e+01	5.569e+01	9.493e−01	2.894e−01	8.280e−01
stop-retract	7.081e+01	6.509e+01	5.628e+01	3.000e−01	5.334e−01	1.338e+00
super-stop	7.486e+01	6.622e+01	4.339e+01	4.877e−01	7.030e−01	4.727e−01
super-zero-g	7.631e+01	6.736e+01	4.438e+01	4.610e−01	8.468e−01	2.369e−01
zero-g	7.471e+01	6.612e+01	4.890e+01	8.304e−01	6.528e−01	5.881e−01

3 criterion 2

Table 9: criterion 2 measured by PRMS device for collisions at velocity 0.04 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	3.900e−01	3.010e−01	7.307e−01	1.169e−01	9.356e−02	2.140e−02
admittance-stop	1.435e−01	5.857e−01	5.905e−01	1.451e−02	5.005e−02	8.075e−02
cart-retraction	0.000e+00	0.000e+00	2.671e−02	0.000e+00	0.000e+00	2.313e−02
joint-retraction	1.488e−01	1.085e−01	2.999e−01	2.444e−02	1.353e−02	3.486e−02
stop	1.414e+00	4.141e+00	5.768e+00	1.984e−01	1.816e−01	1.909e−01
stop-retract	1.339e−01	1.557e−01	2.105e−01	2.643e−02	3.307e−02	9.714e−02
super-stop	7.230e−01	5.774e−01	5.165e−01	1.651e−01	7.699e−02	2.496e−01
super-zero-g	2.417e−03	8.104e−01	1.847e−01	4.636e−03	8.879e−02	4.666e−02
zero-g	5.060e−01	1.500e+00	1.099e+00	2.200e−01	2.183e−01	1.086e−01

Table 10: criterion 2 measured by PRMS device for collisions at velocity 0.08 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.641e−01	7.631e−02	7.085e−02	3.771e−02	2.125e−02	2.971e−02
admittance-stop	1.640e−01	2.009e−02	1.235e−01	1.496e−02	2.158e−02	2.953e−02
cart-retraction	1.449e−01	1.269e−01	2.765e−01	2.723e−02	4.424e−03	5.422e−02
joint-retraction	1.565e−01	9.747e−02	5.473e−01	4.424e−02	4.513e−02	1.032e−01
stop	7.851e+00	1.002e+01	1.055e+01	8.832e−01	5.415e−01	4.150e−01
stop-retract	1.394e−01	9.528e−02	4.310e−01	3.216e−02	3.396e−02	4.904e−02
super-stop	1.250e−01	0.000e+00	2.743e−01	0.000e+00	0.000e+00	4.512e−02
super-zero-g	1.627e−01	0.000e+00	1.580e−01	4.535e−02	0.000e+00	4.648e−02
zero-g	0.000e+00	0.000e+00	4.829e−02	0.000e+00	0.000e+00	1.750e−02

Table 11: criterion 2 measured by PRMS device for collisions at velocity 0.15 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	0.000e+00	0.000e+00	3.834e−01	0.000e+00	0.000e+00	3.907e−02
admittance-stop	1.250e−01	1.340e−01	4.375e−01	0.000e+00	1.216e−02	4.452e−02
cart-retraction	1.402e−01	1.382e−01	3.326e−01	2.819e−02	2.348e−02	5.917e−02
joint-retraction	1.491e−01	2.287e−01	5.660e−01	3.573e−02	3.603e−02	5.365e−02
stop	2.215e+01	2.307e+01	2.041e+01	1.247e+00	2.292e+00	2.915e−01
stop-retract	1.693e−01	1.099e−01	8.530e−01	4.286e−02	2.594e−02	6.440e−02
super-stop	1.252e−01	1.382e−01	4.972e−01	5.556e−04	1.394e−02	6.167e−02
super-zero-g	1.273e−01	7.175e−02	3.516e−01	9.138e−03	4.399e−02	3.847e−02
zero-g	1.255e−01	0.000e+00	4.235e−01	1.134e−03	0.000e+00	3.633e−02

Table 12: criterion 2 measured by PRMS device for collisions at velocity 0.25 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.255e−01	1.207e−01	8.349e−01	1.653e−03	4.381e−03	1.129e−01
admittance-stop	1.363e−01	1.367e−01	1.128e+00	1.953e−02	1.347e−02	8.142e−02
cart-retraction	1.250e−01	1.285e−01	9.240e−01	0.000e+00	2.094e−02	7.328e−02
joint-retraction	1.628e−01	1.306e−01	9.033e−01	4.908e−02	8.106e−03	1.384e−01
stop	4.923e+01	5.423e+01	5.045e+01	1.109e+00	8.105e−01	8.881e−01
stop-retract	1.500e−01	1.237e−01	1.082e+00	4.144e−02	3.194e−03	4.923e−01
super-stop	1.313e−01	6.173e−02	4.550e−01	1.956e−02	3.761e−02	5.748e−02
super-zero-g	1.251e−01	2.552e−02	5.932e−01	9.874e−05	2.613e−02	8.387e−02
zero-g	1.145e+00	1.302e−01	4.290e−01	5.749e−01	8.194e−03	4.923e−02

4 criterion 3

Table 13: criterion 3 measured by PRMS device for collisions at velocity 0.04 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	4.128e−01	4.602e−01	1.119e+00	8.893e−02	7.586e−02	2.068e−02
admittance-stop	3.235e−01	7.347e−01	1.086e+00	9.031e−03	4.112e−02	6.025e−02
cart-retraction	1.298e−01	2.300e−01	5.458e−01	5.895e−03	8.457e−03	3.108e−02
joint-retraction	2.926e−01	3.644e−01	9.120e−01	2.490e−02	1.610e−02	3.551e−02
stop	1.523e+00	4.309e+00	6.027e+00	1.926e−01	1.867e−01	1.837e−01
stop-retract	4.181e−01	6.111e−01	1.075e+00	3.498e−02	4.579e−02	1.260e−01
super-stop	8.941e−01	7.124e−01	1.102e+00	1.072e−01	5.874e−02	1.992e−01
super-zero-g	5.688e−02	9.045e−01	6.481e−01	5.677e−03	8.885e−02	3.873e−02
zero-g	6.314e−01	1.714e+00	1.551e+00	2.266e−01	1.947e−01	9.224e−02

Table 14: criterion 3 measured by PRMS device for collisions at velocity 0.08 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.790e−01	1.777e−01	6.037e−01	3.382e−02	1.731e−02	3.024e−02
admittance-stop	2.160e−01	1.357e−01	7.931e−01	1.480e−02	1.929e−02	2.251e−02
cart-retraction	1.630e−01	2.681e−01	9.102e−01	2.607e−02	9.969e−03	5.584e−02
joint-retraction	1.777e−01	2.247e−01	1.224e+00	4.020e−02	4.840e−02	1.030e−01
stop	7.784e+00	1.010e+01	1.074e+01	8.921e−01	5.430e−01	4.017e−01
stop-retract	6.806e−01	8.301e−01	1.810e+00	5.970e−02	3.558e−02	4.006e−02
super-stop	1.679e−01	9.597e−02	9.657e−01	7.550e−03	6.753e−03	4.068e−02
super-zero-g	1.878e−01	1.101e−01	8.022e−01	3.957e−02	1.196e−02	5.296e−02
zero-g	2.700e−02	1.389e−01	7.654e−01	5.049e−03	4.574e−03	1.994e−02

Table 15: criterion 3 measured by PRMS device for collisions at velocity 0.15 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.443e−02	1.256e−01	1.280e+00	7.664e−04	9.412e−03	4.306e−02
admittance-stop	1.581e−01	2.670e−01	1.381e+00	9.014e−03	1.697e−02	3.227e−02
cart-retraction	1.650e−01	2.510e−01	1.198e+00	2.617e−02	2.517e−02	6.232e−02
joint-retraction	1.762e−01	3.520e−01	1.421e+00	3.314e−02	6.863e−02	4.317e−02
stop	2.256e+01	2.324e+01	2.069e+01	1.252e+00	2.280e+00	2.903e−01
stop-retract	1.521e+00	1.633e+00	3.245e+00	5.310e−02	4.433e−02	6.208e−02
super-stop	1.617e−01	2.104e−01	1.432e+00	6.036e−03	1.778e−02	5.815e−02
super-zero-g	1.625e−01	1.554e−01	1.185e+00	9.881e−03	4.281e−02	4.097e−02
zero-g	1.468e−01	1.197e−01	1.594e+00	3.263e−03	8.330e−03	3.536e−02

Table 16: criterion 3 measured by PRMS device for collisions at velocity 0.25 m/s.

	mean [N]			standard deviation [N]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.864e−01	2.812e−01	2.114e+00	1.073e−02	1.672e−02	2.206e−01
admittance-stop	1.804e−01	3.110e−01	2.412e+00	2.092e−02	1.658e−02	5.283e−02
cart-retraction	1.595e−01	2.521e−01	2.318e+00	4.882e−03	2.917e−02	5.327e−02
joint-retraction	2.077e−01	2.354e−01	2.177e+00	4.514e−02	7.449e−03	1.406e−01
stop	5.037e+01	5.440e+01	5.090e+01	1.136e+00	8.081e−01	8.790e−01
stop-retract	2.864e+00	2.927e+00	4.817e+00	1.035e−01	5.329e−02	4.801e−01
super-stop	1.735e−01	1.285e−01	1.644e+00	2.042e−02	3.466e−02	5.653e−02
super-zero-g	1.700e−01	1.012e−01	1.821e+00	1.103e−02	2.454e−02	7.347e−02
zero-g	1.035e+00	2.387e−01	2.149e+00	4.810e−01	1.325e−02	5.300e−02

5 criterion 4

5.1 Evaluated with data from PRMS device

Table 17: criterion 4 measured by PRMS device for collisions at velocity 0.04 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	5.798e−03	6.860e−03	1.516e−02	6.012e−04	7.745e−04	2.049e−04
admittance-stop	7.076e−03	7.824e−03	1.725e−02	3.169e−04	4.521e−04	8.955e−04
cart-retraction	5.704e−03	7.769e−03	1.362e−02	3.037e−04	2.875e−04	4.282e−04
joint-retraction	5.580e−03	7.689e−03	1.415e−02	4.119e−04	3.512e−04	2.054e−04
stop	5.689e−03	6.667e−03	1.114e−02	3.901e−04	4.119e−04	3.284e−04
stop-retract	6.498e−03	7.123e−03	1.450e−02	2.357e−04	8.337e−04	6.918e−04
super-stop	7.655e−03	8.132e−03	1.684e−02	9.073e−04	4.993e−04	8.175e−04
super-zero-g	3.343e−03	8.870e−03	1.288e−02	1.823e−04	5.358e−04	4.480e−04
zero-g	6.523e−03	6.850e−03	1.254e−02	3.251e−04	2.131e−04	4.323e−04

Table 18: criterion 4 measured by PRMS device for collisions at velocity 0.08 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	2.402e−02	1.901e−02	3.355e−02	1.233e−03	8.259e−04	8.573e−04
admittance-stop	2.569e−02	1.813e−02	4.316e−02	1.015e−03	5.116e−04	1.031e−03
cart-retraction	2.257e−02	2.163e−02	3.413e−02	7.779e−04	8.776e−04	6.124e−04
joint-retraction	2.215e−02	2.077e−02	3.893e−02	6.942e−04	6.530e−04	1.060e−03
stop	2.418e−02	2.434e−02	4.512e−02	1.029e−03	1.585e−03	3.873e−03
stop-retract	2.101e−02	1.919e−02	4.228e−02	1.134e−03	9.686e−04	1.090e−03
super-stop	2.455e−02	1.893e−02	3.507e−02	7.517e−04	9.333e−04	1.070e−03
super-zero-g	2.330e−02	1.971e−02	3.522e−02	1.289e−03	8.761e−04	9.246e−04
zero-g	2.204e−02	1.544e−02	2.982e−02	7.747e−04	9.423e−04	5.589e−04

Table 19: criterion 4 measured by PRMS device for collisions at velocity 0.15 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	6.526e−02	6.197e−02	1.238e−01	4.336e−03	3.351e−03	2.855e−03
admittance-stop	6.961e−02	6.239e−02	1.004e−01	2.881e−03	2.776e−03	2.215e−03
cart-retraction	6.368e−02	5.972e−02	8.848e−02	4.105e−03	3.092e−03	2.350e−03
joint-retraction	6.312e−02	5.761e−02	9.159e−02	3.017e−03	3.561e−03	2.136e−03
stop	8.370e−02	9.106e−02	1.552e−01	3.866e−03	1.383e−02	5.270e−03
stop-retract	6.970e−02	6.092e−02	1.103e−01	3.548e−03	4.004e−03	1.571e−03
super-stop	6.231e−02	6.018e−02	9.027e−02	3.593e−03	1.564e−03	2.430e−03
super-zero-g	7.406e−02	6.033e−02	8.879e−02	2.397e−03	1.625e−03	1.226e−03
zero-g	6.951e−02	5.213e−02	8.464e−02	4.056e−03	2.284e−03	2.404e−03

Table 20: criterion 4 measured by PRMS device for collisions at velocity 0.25 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.561e−01	1.700e−01	2.978e−01	1.112e−02	6.916e−03	4.486e−02
admittance-stop	1.494e−01	1.627e−01	2.566e−01	1.040e−02	6.858e−03	5.291e−03
cart-retraction	1.402e−01	1.533e−01	2.127e−01	9.396e−03	4.409e−03	2.642e−03
joint-retraction	1.367e−01	1.594e−01	2.230e−01	7.958e−03	8.754e−03	6.023e−03
stop	3.166e−01	3.944e−01	7.368e−01	1.542e−02	1.416e−02	2.591e−02
stop-retract	1.615e−01	1.584e−01	2.646e−01	7.423e−03	1.389e−02	6.921e−03
super-stop	1.409e−01	1.537e−01	2.047e−01	1.350e−02	8.066e−03	4.939e−03
super-zero-g	1.467e−01	1.583e−01	2.103e−01	6.556e−03	6.517e−03	4.630e−03
zero-g	1.435e−01	1.431e−01	2.058e−01	1.112e−02	6.524e−03	4.630e−03

5.2 Evaluated with data from robot

Table 21: criterion 4 measured by robot for collisions at velocity 0.04 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	9.657e−03	9.053e−03	1.375e−02	1.046e−03	1.115e−03	2.798e−04
admittance-stop	7.992e−03	7.810e−03	1.074e−02	3.550e−04	3.936e−04	7.068e−04
cart-retraction	1.497e−03	2.622e−03	6.446e−03	2.690e−04	2.449e−04	4.031e−04
joint-retraction	1.410e−03	2.302e−03	6.117e−03	9.354e−05	8.540e−05	1.465e−04
stop	1.321e−03	2.877e−03	6.456e−03	1.361e−04	1.910e−04	1.981e−04
stop-retract	1.894e−03	2.261e−03	6.056e−03	1.187e−04	3.417e−04	3.364e−04
super-stop	5.723e−03	5.280e−03	7.986e−03	1.418e−04	1.839e−04	4.989e−04
super-zero-g	5.241e−03	6.083e−03	8.859e−03	3.376e−04	2.436e−04	2.479e−04
zero-g	1.686e−03	1.852e−03	5.530e−03	1.012e−04	2.569e−04	2.070e−04

Table 22: criterion 4 measured by robot for collisions at velocity 0.08 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.935e−02	1.960e−02	2.890e−02	8.859e−04	7.365e−04	3.682e−04
admittance-stop	2.180e−02	1.034e−02	2.372e−02	6.211e−04	7.765e−03	6.601e−04
cart-retraction	2.721e−03	3.859e−03	1.221e−02	1.588e−04	1.699e−04	3.056e−04
joint-retraction	2.417e−03	3.370e−03	1.211e−02	1.438e−04	1.710e−04	5.393e−04
stop	6.932e−03	7.021e−03	1.627e−02	4.969e−04	3.788e−04	3.904e−04
stop-retract	4.911e−03	3.948e−03	1.429e−02	2.121e−04	1.659e−04	2.735e−04
super-stop	8.319e−03	5.856e−03	1.380e−02	6.364e−04	3.848e−04	5.653e−04
super-zero-g	6.587e−03	8.198e−03	1.696e−02	5.208e−04	1.013e−03	7.622e−04
zero-g	3.344e−03	2.926e−03	1.182e−02	1.341e−04	2.176e−04	4.958e−04

Table 23: criterion 4 measured by robot for collisions at velocity 0.15 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	3.782e−02	3.492e−02	5.524e−02	1.166e−03	7.592e−04	1.774e−03
admittance-stop	7.866e−03	6.940e−03	2.981e−02	4.624e−04	5.863e−04	3.931e−04
cart-retraction	5.282e−03	5.994e−03	2.493e−02	2.606e−04	4.521e−04	5.598e−04
joint-retraction	5.032e−03	6.678e−03	2.468e−02	2.214e−04	3.704e−04	4.991e−04
stop	2.181e−02	1.424e−02	3.097e−02	1.162e−03	1.090e−03	6.359e−04
stop-retract	1.517e−02	1.134e−02	3.321e−02	1.006e−03	9.182e−04	7.926e−04
super-stop	6.849e−03	6.432e−03	2.809e−02	1.953e−04	3.315e−04	4.623e−04
super-zero-g	9.436e−03	1.089e−02	2.623e−02	3.991e−04	7.859e−04	1.031e−03
zero-g	7.416e−03	7.740e−03	2.714e−02	5.276e−04	3.484e−04	7.424e−04

Table 24: criterion 4 measured by robot for collisions at velocity 0.25 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	6.158e−02	7.056e−02	1.087e−01	2.399e−03	3.694e−03	2.021e−02
admittance-stop	1.336e−02	1.383e−02	6.727e−02	6.078e−04	6.898e−04	1.734e−03
cart-retraction	1.090e−02	1.418e−02	5.699e−02	3.952e−04	5.046e−04	1.017e−03
joint-retraction	1.115e−02	1.372e−02	5.925e−02	1.152e−03	6.518e−04	7.686e−04
stop	4.978e−02	3.328e−02	8.933e−02	3.981e−03	1.800e−03	3.951e−03
stop-retract	4.109e−02	2.616e−02	7.673e−02	2.171e−03	3.280e−03	9.466e−04
super-stop	1.154e−02	1.315e−02	5.315e−02	3.907e−04	6.455e−04	1.784e−03
super-zero-g	1.217e−02	1.349e−02	5.455e−02	4.699e−04	6.493e−04	7.208e−04
zero-g	1.788e−02	1.415e−02	6.038e−02	1.087e−03	5.911e−04	1.395e−03

5.3 Evaluated with data from robot and applied deadzone

Table 25: criterion 4 measured by robot with deadzone of 2 N applied to forces for collisions at velocity 0.04 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	3.335e−04	6.440e−04	2.871e−03	7.193e−05	1.638e−04	1.177e−04
admittance-stop	7.585e−04	6.836e−04	2.617e−03	6.994e−05	9.485e−05	1.190e−04
cart-retraction	4.060e−04	8.723e−04	2.983e−03	9.358e−05	1.163e−04	2.032e−04
joint-retraction	3.811e−04	7.525e−04	2.651e−03	7.125e−05	5.906e−05	1.305e−04
stop	4.425e−04	1.236e−03	3.283e−03	3.983e−05	1.194e−04	1.192e−04
stop-retract	7.718e−04	8.464e−04	2.686e−03	6.638e−05	1.869e−04	2.072e−04
super-stop	8.880e−04	6.252e−04	2.553e−03	1.083e−04	1.126e−04	2.007e−04
super-zero-g	3.533e−04	6.714e−04	2.286e−03	4.177e−05	1.744e−04	1.008e−04
zero-g	5.699e−04	6.356e−04	2.519e−03	8.782e−05	1.503e−04	1.591e−04

Table 26: criterion 4 measured by robot with deadzone of 2 N applied to forces for collisions at velocity 0.08 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.221e−03	1.095e−03	7.890e−03	1.300e−04	1.083e−04	2.893e−04
admittance-stop	2.561e−03	1.123e−03	7.350e−03	1.951e−04	9.695e−05	1.460e−04
cart-retraction	1.283e−03	1.471e−03	6.407e−03	1.056e−04	9.133e−05	2.520e−04
joint-retraction	1.201e−03	1.347e−03	6.377e−03	1.054e−04	1.068e−04	3.423e−04
stop	4.991e−03	4.507e−03	9.823e−03	4.493e−04	3.345e−04	2.715e−04
stop-retract	3.318e−03	1.890e−03	7.998e−03	1.707e−04	1.296e−04	2.086e−04
super-stop	2.099e−03	1.184e−03	7.893e−03	2.175e−04	8.430e−05	4.977e−04
super-zero-g	1.238e−03	1.288e−03	5.863e−03	1.164e−04	1.238e−04	2.574e−04
zero-g	1.491e−03	1.144e−03	6.099e−03	1.147e−04	1.152e−04	2.791e−04

Table 27: criterion 4 measured by robot with deadzone of 2 N applied to forces for collisions at velocity 0.15 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	5.991e−03	4.967e−03	1.865e−02	8.244e−04	4.965e−04	1.201e−03
admittance-stop	5.256e−03	4.049e−03	2.054e−02	3.792e−04	3.684e−04	3.844e−04
cart-retraction	3.084e−03	3.551e−03	1.631e−02	1.939e−04	3.008e−04	5.172e−04
joint-retraction	3.003e−03	3.873e−03	1.595e−02	1.325e−04	2.751e−04	4.222e−04
stop	1.866e−02	1.098e−02	2.062e−02	1.032e−03	1.004e−03	5.569e−04
stop-retract	1.231e−02	8.311e−03	2.327e−02	1.025e−03	6.992e−04	6.960e−04
super-stop	4.392e−03	3.731e−03	1.912e−02	7.987e−05	1.780e−04	4.766e−04
super-zero-g	4.203e−03	3.572e−03	1.560e−02	3.438e−04	2.297e−04	7.859e−04
zero-g	4.064e−03	3.505e−03	1.750e−02	1.953e−04	2.139e−04	7.266e−04

Table 28: criterion 4 measured by robot with deadzone of 2 N applied to forces for collisions at velocity 0.25 m/s.

	mean [J]			standard deviation [J]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.831e−02	2.563e−02	6.106e−02	1.406e−03	2.093e−03	1.221e−02
admittance-stop	9.950e−03	9.539e−03	5.380e−02	5.511e−04	4.396e−04	1.466e−03
cart-retraction	7.878e−03	9.635e−03	4.462e−02	3.609e−04	4.488e−04	7.978e−04
joint-retraction	8.106e−03	9.382e−03	4.659e−02	1.025e−03	4.224e−04	6.231e−04
stop	4.476e−02	2.563e−02	6.817e−02	3.606e−03	1.614e−03	3.753e−03
stop-retract	3.704e−02	2.174e−02	6.295e−02	2.090e−03	2.970e−03	7.975e−04
super-stop	8.510e−03	8.882e−03	4.125e−02	2.475e−04	4.683e−04	1.616e−03
super-zero-g	9.179e−03	9.379e−03	4.247e−02	4.003e−04	5.588e−04	5.718e−04
zero-g	9.149e−03	9.295e−03	4.798e−02	7.258e−04	4.749e−04	1.113e−03

6 criterion 5

Table 29: criterion 5 measured by PRMS device for collisions at velocity 0.04 m/s.

	mean [s]			standard deviation [s]		
reflex	hard	medium	soft	hard	medium	soft
admittance	7.155e−02	9.080e−02	1.588e−01	1.833e−03	1.549e−03	1.975e−03
admittance-stop	8.360e−02	9.025e−02	1.519e−01	2.132e−03	1.253e−03	1.370e−03
cart-retraction	7.315e−02	8.905e−02	1.368e−01	1.203e−03	1.992e−03	2.336e−03
joint-retraction	7.360e−02	9.170e−02	1.442e−01	1.506e−03	1.494e−03	3.093e−03
stop	8.365e−02	1.993e+00	1.991e+00	1.492e−03	2.635e−04	3.333e−04
stop-retract	1.740e−01	1.810e−01	2.321e−01	2.179e−03	2.608e−03	2.066e−03
super-stop	1.890e−02	8.685e−02	1.494e−01	3.578e−02	1.395e−03	3.013e−03
super-zero-g	6.485e−02	9.035e−02	1.444e−01	9.733e−04	1.842e−03	2.846e−03
zero-g	7.780e−02	2.922e−01	1.774e−01	4.328e−03	5.976e−01	1.612e−03

Table 30: criterion 5 measured by PRMS device for collisions at velocity 0.08 m/s.

	mean [s]			standard deviation [s]		
reflex	hard	medium	soft	hard	medium	soft
admittance	5.355e−02	6.640e−02	1.186e−01	5.503e−04	3.944e−04	1.029e−03
admittance-stop	5.775e−02	6.520e−02	1.094e−01	7.546e−04	3.496e−04	3.944e−04
cart-retraction	5.265e−02	6.730e−02	1.085e−01	3.375e−04	4.830e−04	7.976e−04
joint-retraction	5.115e−02	6.495e−02	1.030e−01	7.472e−04	8.317e−04	1.764e−03
stop	4.457e−01	1.993e+00	1.993e+00	8.156e−01	2.582e−04	2.582e−04
stop-retract	1.506e−01	1.600e−01	1.965e−01	6.583e−04	6.433e−04	9.129e−04
super-stop	5.480e−02	6.380e−02	1.114e−01	8.233e−04	4.216e−04	1.001e−03
super-zero-g	5.135e−02	6.565e−02	1.128e−01	8.835e−04	8.515e−04	9.443e−04
zero-g	5.435e−02	7.585e−02	1.345e−01	1.132e−03	5.297e−04	1.039e−03

Table 31: criterion 5 measured by PRMS device for collisions at velocity 0.15 m/s.

	mean [s]			standard deviation [s]		
reflex	hard	medium	soft	hard	medium	soft
admittance	4.560e−02	6.045e−02	9.580e−02	3.944e−04	5.503e−04	5.375e−04
admittance-stop	4.775e−02	6.030e−02	9.585e−02	5.401e−04	3.496e−04	3.375e−04
cart-retraction	4.585e−02	6.200e−02	1.036e−01	2.415e−04	4.714e−04	8.835e−04
joint-retraction	4.555e−02	6.115e−02	9.550e−02	5.503e−04	2.887e−03	5.774e−04
stop	1.993e+00	1.993e+00	1.993e+00	2.108e−04	2.415e−04	1.581e−04
stop-retract	1.459e−01	1.579e−01	1.870e−01	4.378e−04	1.212e−03	7.619e−04
super-stop	4.665e−02	5.780e−02	1.036e−01	7.091e−04	6.749e−04	4.116e−04
super-zero-g	4.765e−02	5.910e−02	1.034e−01	3.375e−04	1.022e−03	5.297e−04
zero-g	4.870e−02	6.685e−02	1.320e−01	2.582e−04	4.743e−04	4.972e−04

Table 32: criterion 5 measured by PRMS device for collisions at velocity 0.25 m/s.

	mean [s]			standard deviation [s]		
reflex	hard	medium	soft	hard	medium	soft
admittance	4.660e−02	5.810e−02	9.085e−02	1.174e−03	5.676e−04	1.334e−03
admittance-stop	4.395e−02	5.820e−02	9.135e−02	4.378e−04	4.216e−04	6.258e−04
cart-retraction	4.530e−02	5.975e−02	1.042e−01	3.496e−04	3.536e−04	5.401e−04
joint-retraction	4.380e−02	5.840e−02	9.640e−02	8.563e−04	3.162e−04	7.379e−04
stop	1.993e+00	1.993e+00	1.993e+00	2.635e−04	2.582e−04	2.108e−04
stop-retract	1.459e−01	1.607e−01	1.876e−01	5.164e−04	1.206e−03	2.196e−03
super-stop	4.225e−02	5.530e−02	9.930e−02	2.635e−04	4.830e−04	4.216e−04
super-zero-g	4.110e−02	5.595e−02	1.001e−01	5.164e−04	9.265e−04	2.108e−04
zero-g	4.255e−02	6.255e−02	1.253e−01	2.838e−04	5.503e−04	5.401e−04

7 criterion 6

Table 33: criterion 6 measured by PRMS device for collisions at velocity 0.04 m/s.

	mean [Ns]			standard deviation [Ns]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.485e+00	1.411e+00	2.437e+00	1.776e−01	1.451e−01	4.347e−02
admittance-stop	1.144e+00	1.971e+00	2.377e+00	9.442e−03	8.277e−02	1.150e−01
cart-retraction	9.406e−01	9.603e−01	1.334e+00	7.723e−03	1.258e−02	5.584e−02
joint-retraction	1.261e+00	1.219e+00	2.029e+00	4.559e−02	3.307e−02	6.957e−02
stop	3.682e+00	8.906e+00	1.197e+01	3.764e−01	3.637e−01	3.598e−01
stop-retract	1.388e+00	1.729e+00	2.359e+00	6.954e−02	8.380e−02	2.481e−01
super-stop	2.244e+00	1.935e+00	2.417e+00	2.323e−01	1.181e−01	3.818e−01
super-zero-g	6.361e−01	2.282e+00	1.513e+00	1.168e−02	1.747e−01	7.467e−02
zero-g	1.939e+00	3.885e+00	3.280e+00	4.012e−01	3.845e−01	1.808e−01

Table 34: criterion 6 measured by PRMS device for collisions at velocity 0.08 m/s.

	mean [Ns]			standard deviation [Ns]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.951e+00	1.547e+00	1.661e+00	6.816e−02	3.619e−02	6.075e−02
admittance-stop	1.840e+00	1.539e+00	2.105e+00	2.236e−02	3.732e−02	4.667e−02
cart-retraction	1.924e+00	1.686e+00	2.336e+00	5.100e−02	2.361e−02	1.062e−01
joint-retraction	1.957e+00	1.635e+00	2.940e+00	7.802e−02	9.027e−02	1.999e−01
stop	1.668e+01	2.074e+01	2.133e+01	1.744e+00	1.046e+00	7.818e−01
stop-retract	2.726e+00	2.894e+00	4.082e+00	1.146e−01	7.011e−02	8.530e−02
super-stop	1.751e+00	1.437e+00	2.449e+00	3.088e−02	2.039e−02	7.724e−02
super-zero-g	1.960e+00	1.395e+00	2.114e+00	8.287e−02	2.938e−02	9.963e−02
zero-g	1.673e+00	1.442e+00	2.043e+00	2.231e−02	1.091e−02	3.446e−02

Table 35: criterion 6 measured by PRMS device for collisions at velocity 0.15 m/s.

	mean [Ns]			standard deviation [Ns]		
reflex	hard	medium	soft	hard	medium	soft
admittance	2.907e+00	2.690e+00	3.653e+00	2.242e−02	4.699e−02	9.006e−02
admittance-stop	3.009e+00	3.043e+00	3.875e+00	2.593e−02	3.542e−02	6.828e−02
cart-retraction	3.130e+00	2.843e+00	3.478e+00	4.825e−02	6.947e−02	1.227e−01
joint-retraction	3.170e+00	3.067e+00	3.913e+00	7.409e−02	1.635e−01	8.908e−02
stop	4.667e+01	4.739e+01	4.119e+01	2.436e+00	4.506e+00	5.664e−01
stop-retract	5.674e+00	5.671e+00	7.472e+00	1.147e−01	8.307e−02	1.165e−01
super-stop	2.828e+00	2.826e+00	3.964e+00	2.220e−02	5.476e−02	1.220e−01
super-zero-g	3.173e+00	2.640e+00	3.457e+00	3.905e−02	9.366e−02	8.021e−02
zero-g	3.243e+00	2.594e+00	4.262e+00	2.548e−02	2.990e−02	7.108e−02

Table 36: criterion 6 measured by PRMS device for collisions at velocity 0.25 m/s.

	mean [Ns]			standard deviation [Ns]		
reflex	hard	medium	soft	hard	medium	soft
admittance	4.602e+00	4.920e+00	6.121e+00	8.175e−02	5.500e−02	5.275e−01
admittance-stop	4.615e+00	4.942e+00	6.742e+00	5.991e−02	6.355e−02	9.578e−02
cart-retraction	4.311e+00	4.629e+00	6.528e+00	4.047e−02	8.490e−02	1.012e−01
joint-retraction	4.399e+00	4.594e+00	6.262e+00	1.242e−01	2.848e−02	2.725e−01
stop	1.022e+02	1.100e+02	1.010e+02	2.220e+00	1.573e+00	1.722e+00
stop-retract	9.989e+00	9.956e+00	1.133e+01	2.222e−01	1.048e−01	9.824e−01
super-stop	4.249e+00	4.195e+00	5.214e+00	5.331e−02	7.164e−02	1.111e−01
super-zero-g	4.284e+00	4.232e+00	5.581e+00	5.894e−02	8.532e−02	1.424e−01
zero-g	6.006e+00	4.543e+00	6.218e+00	9.220e−01	6.275e−02	1.008e−01

8 criterion 7

8.1 Evaluated with respect to contact location

Table 37: criterion 7 measured by robot with respect to the point of contact for collisions at velocity 0.04 m/s.

	mean [m]			standard deviation [m]		
reflex	hard	medium	soft	hard	medium	soft
admittance	8.157e−03	7.999e−03	8.909e−03	1.981e−04	3.712e−04	8.944e−05
admittance-stop	7.906e−03	7.942e−03	6.855e−03	1.411e−04	3.084e−04	2.207e−04
cart-retraction	7.346e−02	7.265e−02	7.246e−02	5.158e−04	4.191e−04	3.821e−04
joint-retraction	3.984e−02	3.897e−02	3.791e−02	1.842e−04	1.846e−04	2.373e−04
stop	4.989e−04	9.137e−04	1.596e−03	1.687e−05	3.446e−05	4.211e−05
stop-retract	3.856e−02	3.875e−02	3.767e−02	2.926e−04	1.834e−04	3.086e−04
super-stop	4.792e−03	4.343e−03	4.953e−03	2.908e−04	1.453e−04	5.913e−04
super-zero-g	6.028e−03	4.442e−03	4.606e−03	1.874e−04	2.038e−04	3.991e−04
zero-g	6.482e−04	9.357e−04	1.980e−03	7.307e−05	3.367e−05	7.560e−05

Table 38: criterion 7 measured by robot with respect to the point of contact for collisions at velocity 0.08 m/s.

	mean [m]			standard deviation [m]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.965e−02	1.917e−02	1.710e−02	4.166e−04	3.063e−04	3.672e−04
admittance-stop	1.934e−02	2.072e−02	1.661e−02	1.812e−04	1.327e−03	2.570e−04
cart-retraction	7.308e−02	7.363e−02	7.208e−02	1.446e−04	2.180e−04	4.275e−04
joint-retraction	3.800e−02	3.644e−02	3.587e−02	1.346e−04	7.437e−05	2.485e−04
stop	8.656e−04	1.566e−03	3.924e−03	4.964e−05	7.648e−05	2.624e−04
stop-retract	3.878e−02	3.846e−02	3.761e−02	1.012e−04	7.594e−05	1.979e−04
super-stop	1.788e−02	1.672e−02	2.018e−02	6.741e−04	4.898e−04	8.346e−04
super-zero-g	2.297e−02	1.253e−02	1.413e−02	4.715e−04	5.917e−04	8.417e−04
zero-g	2.498e−03	1.342e−03	2.737e−03	1.906e−04	1.687e−05	2.691e−05

Table 39: criterion 7 measured by robot with respect to the point of contact for collisions at velocity 0.15 m/s.

	mean [m]			standard deviation [m]		
reflex	hard	medium	soft	hard	medium	soft
admittance	4.168e−02	3.908e−02	3.686e−02	1.947e−04	5.316e−04	5.029e−04
admittance-stop	5.691e−02	5.626e−02	5.398e−02	6.366e−04	3.394e−04	3.400e−04
cart-retraction	7.438e−02	7.330e−02	7.226e−02	4.763e−04	2.707e−04	1.011e−04
joint-retraction	3.604e−02	3.533e−02	3.340e−02	9.189e−05	3.807e−04	1.260e−04
stop	1.757e−03	2.639e−03	7.464e−03	9.137e−05	1.917e−04	1.761e−04
stop-retract	3.917e−02	3.791e−02	3.696e−02	1.890e−04	1.039e−04	2.025e−04
super-stop	2.927e−02	3.323e−02	2.972e−02	3.244e−04	5.555e−04	3.913e−04
super-zero-g	6.478e−02	4.388e−02	4.072e−02	2.161e−03	1.424e−03	1.094e−03
zero-g	7.789e−03	4.477e−03	9.832e−03	1.819e−04	2.721e−04	1.515e−04

Table 40: criterion 7 measured by robot with respect to the point of contact for collisions at velocity 0.25 m/s.

	mean [m]			standard deviation [m]		
reflex	hard	medium	soft	hard	medium	soft
admittance	6.736e−02	7.143e−02	6.334e−02	1.441e−03	7.727e−04	7.760e−03
admittance-stop	7.643e−02	7.847e−02	7.665e−02	6.759e−04	5.440e−04	1.172e−03
cart-retraction	5.527e−02	5.834e−02	5.677e−02	3.857e−04	3.167e−04	3.634e−04
joint-retraction	3.549e−02	3.477e−02	3.335e−02	1.720e−04	2.038e−04	1.597e−04
stop	2.908e−03	4.944e−03	1.550e−02	1.587e−04	1.324e−04	4.566e−04
stop-retract	3.920e−02	3.739e−02	3.519e−02	1.454e−04	1.492e−04	2.384e−04
super-stop	3.720e−02	4.359e−02	3.985e−02	9.290e−04	6.620e−04	4.352e−04
super-zero-g	7.351e−02	9.329e−02	8.568e−02	8.374e−04	2.406e−03	6.054e−04
zero-g	1.421e−02	1.109e−02	3.014e−02	1.294e−03	4.559e−04	5.911e−04

8.2 Evaluated with respect to location of contact detection

Table 41: criterion 7 measured by robot with respect to the point of contact detection for collisions at velocity 0.04 m/s.

	mean [m]			standard deviation [m]		
reflex	hard	medium	soft	hard	medium	soft
admittance:	8.311e−03	8.256e−03	1.038e−02	2.024e−04	4.087e−04	1.099e−04
admittance-stop:	8.181e−03	8.266e−03	8.315e−03	1.427e−04	3.176e−04	2.112e−04
cart-retraction:	7.400e−02	7.362e−02	7.453e−02	5.174e−04	3.927e−04	3.721e−04
joint-retraction:	4.006e−02	3.941e−02	3.948e−02	1.903e−04	1.721e−04	2.262e−04
stop:	4.728e−04	9.106e−04	1.594e−03	1.820e−05	3.351e−05	4.202e−05
stop-retract:	3.883e−02	3.912e−02	3.940e−02	3.073e−04	1.798e−04	3.188e−04
super-stop:	5.404e−03	5.183e−03	6.959e−03	2.702e−04	1.248e−04	5.963e−04
super-zero-g:	6.364e−03	5.206e−03	6.272e−03	1.894e−04	1.499e−04	3.968e−04
zero-g:	7.735e−04	9.488e−04	1.977e−03	3.140e−05	6.322e−05	7.397e−05

Table 42: criterion 7 measured by robot with respect to the point of contact detection for collisions at velocity 0.08 m/s.

	mean [m]			standard deviation [m]		
reflex	hard	medium	soft	hard	medium	soft
admittance:	1.997e−02	1.960e−02	1.899e−02	4.167e−04	3.066e−04	3.611e−04
admittance-stop:	1.963e−02	2.112e−02	1.845e−02	1.757e−04	1.321e−03	2.625e−04
cart-retraction:	7.397e−02	7.495e−02	7.480e−02	1.494e−04	2.223e−04	4.404e−04
joint-retraction:	3.833e−02	3.695e−02	3.793e−02	1.406e−04	7.466e−05	2.561e−04
stop:	8.613e−04	1.411e−03	3.671e−03	4.971e−05	8.063e−05	2.585e−04
stop-retract:	3.900e−02	3.894e−02	4.004e−02	9.519e−05	4.699e−05	2.081e−04
super-stop:	1.862e−02	1.765e−02	2.290e−02	6.367e−04	4.324e−04	8.265e−04
super-zero-g:	2.368e−02	1.371e−02	1.673e−02	4.368e−04	6.226e−04	7.948e−04
zero-g:	3.328e−03	2.246e−03	4.660e−03	1.600e−04	4.960e−05	8.058e−05

Table 43: criterion 7 measured by robot with respect to the point of contact detection for collisions at velocity 0.15 m/s.

	mean [m]			standard deviation [m]		
reflex	hard	medium	soft	hard	medium	soft
admittance:	4.198e−02	3.989e−02	3.933e−02	2.004e−04	5.256e−04	4.424e−04
admittance-stop:	5.709e−02	5.713e−02	5.660e−02	6.085e−04	3.211e−04	3.193e−04
cart-retraction:	7.522e−02	7.489e−02	7.574e−02	4.551e−04	2.183e−04	5.107e−05
joint-retraction:	3.623e−02	3.609e−02	3.589e−02	7.378e−05	3.266e−04	8.304e−05
stop:	1.260e−03	2.076e−03	6.390e−03	6.762e−05	2.530e−04	1.885e−04
stop-retract:	3.942e−02	3.869e−02	4.000e−02	1.725e−04	1.205e−04	2.082e−04
super-stop:	3.016e−02	3.454e−02	3.310e−02	2.904e−04	5.224e−04	4.271e−04
super-zero-g:	6.579e−02	4.534e−02	4.416e−02	2.130e−03	1.432e−03	1.046e−03
zero-g:	8.926e−03	5.833e−03	1.296e−02	1.848e−04	2.715e−04	1.811e−04

Table 44: criterion 7 measured by robot with respect to the point of contact detection for collisions at velocity 0.25 m/s.

	mean [m]			standard deviation [m]		
reflex	hard	medium	soft	hard	medium	soft
admittance:	6.780e−02	7.279e−02	6.670e−02	1.457e−03	7.229e−04	8.027e−03
admittance-stop:	7.673e−02	7.984e−02	8.012e−02	6.563e−04	5.379e−04	1.156e−03
cart-retraction:	5.618e−02	6.021e−02	6.065e−02	3.196e−04	2.822e−04	3.394e−04
joint-retraction:	3.564e−02	3.590e−02	3.634e−02	1.266e−04	1.770e−04	8.514e−05
stop:	2.123e−03	4.259e−03	1.249e−02	1.224e−04	1.292e−04	4.689e−04
stop-retract:	3.949e−02	3.855e−02	3.870e−02	1.710e−04	5.993e−05	7.807e−05
super-stop:	3.806e−02	4.516e−02	4.372e−02	9.185e−04	6.373e−04	4.275e−04
super-zero-g:	7.447e−02	9.516e−02	8.956e−02	8.353e−04	2.347e−03	6.408e−04
zero-g:	1.519e−02	1.302e−02	3.373e−02	1.219e−03	4.972e−04	5.634e−04

9 Criterion 8

Table 45: criterion 8 measured by robot with respect to the point of contact detection for collisions at velocity 0.04 m/s

	mean [m/s]			standard deviation [m/s]		
reflex	hard	medium	soft	hard	medium	soft
admittance:	8.749e−02	6.877e−02	7.229e−02	3.482e−03	2.063e−03	1.182e−03
admittance-stop:	7.945e−02	6.914e−02	6.063e−02	2.435e−03	4.162e−03	1.920e−03
cart-retraction:	1.668e−01	1.736e−01	1.763e−01	1.804e−03	2.262e−03	2.663e−03
joint-retraction:	2.943e−01	2.548e−01	1.396e−01	3.146e−03	3.596e−03	9.454e−03
stop:	4.458e−03	0.000e+00	1.852e−03	4.878e−04	0.000e+00	7.640e−04
stop-retract:	9.836e−02	8.086e−02	2.114e−02	5.405e−03	6.373e−03	3.303e−03
super-stop:	4.380e−02	3.305e−02	1.836e−02	6.064e−03	9.789e−04	1.623e−03
super-zero-g:	5.176e−02	3.112e−02	2.688e−02	1.368e−03	2.103e−03	1.326e−03
zero-g:	5.757e−03	3.878e−03	4.157e−03	9.658e−04	1.453e−03	4.945e−04

Table 46: criterion 8 measured by robot with respect to the point of contact detection for collisions at velocity 0.08 m/s

	mean [m/s]			standard deviation [m/s]		
reflex	hard	medium	soft	hard	medium	soft
admittance:	2.018e−01	2.051e−01	1.085e−01	5.083e−03	4.176e−03	2.758e−03
admittance-stop:	2.015e−01	2.089e−01	1.029e−01	2.723e−03	2.101e−03	2.636e−03
cart-retraction:	1.685e−01	1.806e−01	1.799e−01	7.811e−04	1.130e−03	1.575e−03
joint-retraction:	2.824e−01	2.557e−01	1.988e−01	1.981e−03	2.332e−03	6.451e−03
stop:	4.990e−03	0.000e+00	0.000e+00	2.744e−03	0.000e+00	0.000e+00
stop-retract:	1.351e−01	1.008e−01	4.118e−02	2.967e−03	3.146e−03	3.027e−03
super-stop:	9.684e−02	9.460e−02	8.788e−02	2.076e−03	1.529e−03	2.142e−03
super-zero-g:	1.161e−01	8.518e−02	6.848e−02	1.264e−03	3.036e−03	3.535e−03
zero-g:	2.395e−02	1.486e−02	7.287e−03	2.121e−03	1.997e−03	9.211e−04

Table 47: criterion 8 measured by robot with respect to the point of contact detection for collisions at velocity 0.15 m/s

	mean [m/s]			standard deviation [m/s]		
reflex	hard	medium	soft	hard	medium	soft
admittance:	4.200e−01	4.130e−01	2.082e−01	2.166e−03	6.043e−03	1.858e−03
admittance-stop:	4.108e−01	4.173e−01	3.063e−01	5.006e−03	3.277e−03	3.899e−03
cart-retraction:	1.949e−01	1.878e−01	1.965e−01	2.814e−03	2.230e−03	1.888e−03
joint-retraction:	2.709e−01	2.503e−01	1.738e−01	1.444e−03	3.958e−03	3.497e−03
stop:	0.000e+00	0.000e+00	0.000e+00	0.000e+00	0.000e+00	0.000e+00
stop-retract:	1.362e−01	9.341e−02	4.256e−02	5.001e−03	4.314e−03	4.161e−03
super-stop:	1.792e−01	1.895e−01	1.693e−01	2.509e−03	3.628e−03	1.251e−03
super-zero-g:	2.210e−01	1.766e−01	1.518e−01	4.625e−03	3.575e−03	2.393e−03
zero-g:	6.238e−02	4.570e−02	3.808e−02	1.112e−03	2.521e−03	1.457e−03

Table 48: criterion 8 measured by robot with respect to the point of contact detection for collisions at velocity 0.25 m/s.

	mean [m/s]			standard deviation [m/s]		
reflex	hard	medium	soft	hard	medium	soft
admittance:	6.941e−01	7.577e−01	4.145e−01	1.427e−02	6.154e−03	4.177e−02
admittance-stop:	6.498e−01	6.636e−01	4.269e−01	5.761e−03	4.482e−03	7.180e−03
cart-retraction:	1.971e−01	2.059e−01	2.094e−01	3.328e−03	2.287e−03	2.526e−03
joint-retraction:	2.626e−01	2.515e−01	1.790e−01	2.626e−03	2.321e−03	5.291e−03
stop:	0.000e+00	0.000e+00	0.000e+00	0.000e+00	0.000e+00	0.000e+00
stop-retract:	1.417e−01	7.829e−02	2.885e−02	3.449e−03	2.461e−03	4.363e−03
super-stop:	2.837e−01	3.193e−01	2.044e−01	9.444e−03	6.908e−03	3.520e−03
super-zero-g:	2.892e−01	3.296e−01	2.997e−01	5.567e−03	9.874e−03	1.716e−03
zero-g:	8.299e−02	7.647e−02	9.573e−02	2.412e−03	1.661e−03	1.906e−03

10 Contact velocities

Table 49: Measured contact velocity for collisions planned at velocity 0.04 m/s.

	mean [m/s]			standard deviation [m/s]		
reflex	hard	medium	soft	hard	medium	soft
admittance	4.029e−02	4.078e−02	3.933e−02	2.608e−04	5.353e−04	3.690e−04
admittance-stop	4.108e−02	4.108e−02	4.082e−02	6.978e−04	3.215e−04	4.563e−04
cart-retraction	4.016e−02	4.150e−02	3.877e−02	3.973e−04	4.769e−04	4.640e−04
joint-retraction	3.938e−02	4.064e−02	3.985e−02	5.568e−04	2.995e−04	9.640e−04
stop	3.991e−02	4.124e−02	4.032e−02	3.631e−04	3.382e−04	3.230e−04
stop-retract	4.081e−02	4.138e−02	3.942e−02	1.869e−04	3.361e−04	8.469e−04
super-stop	4.119e−02	4.044e−02	4.052e−02	3.142e−04	2.424e−04	7.522e−04
super-zero-g	4.007e−02	4.082e−02	4.014e−02	2.834e−04	6.303e−04	3.758e−04
zero-g	3.896e−02	4.108e−02	3.992e−02	1.902e−04	2.905e−04	5.621e−04

Table 50: Measured contact velocity for collisions planned at velocity 0.08 m/s.

	mean [m/s]			standard deviation [m/s]		
reflex	hard	medium	soft	hard	medium	soft
admittance	8.078e−02	7.912e−02	7.573e−02	4.347e−04	3.242e−04	4.561e−04
admittance-stop	8.042e−02	7.911e−02	7.567e−02	3.883e−04	2.690e−04	5.198e−04
cart-retraction	7.890e−02	7.714e−02	7.609e−02	2.569e−04	3.405e−04	2.034e−04
joint-retraction	8.068e−02	7.859e−02	7.562e−02	2.492e−04	4.361e−04	4.039e−04
stop	8.067e−02	7.843e−02	7.639e−02	5.356e−04	9.580e−04	4.193e−04
stop-retract	7.985e−02	7.916e−02	7.630e−02	9.342e−04	3.230e−04	3.215e−04
super-stop	8.061e−02	7.866e−02	7.612e−02	3.781e−04	2.505e−04	3.836e−04
super-zero-g	8.028e−02	7.828e−02	7.572e−02	5.472e−04	4.337e−04	5.993e−04
zero-g	8.067e−02	7.840e−02	7.569e−02	6.734e−04	4.530e−04	5.420e−04

Table 51: Measured contact velocity for collisions planned at velocity 0.15 m/s.

	mean [m/s]			standard deviation [m/s]		
reflex	hard	medium	soft	hard	medium	soft
admittance	1.518e−01	1.514e−01	1.487e−01	8.320e−04	9.397e−04	1.139e−03
admittance-stop	1.508e−01	1.514e−01	1.486e−01	5.590e−04	5.700e−04	6.914e−04
cart-retraction	1.506e−01	1.506e−01	1.483e−01	9.514e−04	1.012e−03	6.229e−04
joint-retraction	1.507e−01	1.514e−01	1.493e−01	6.099e−04	6.281e−04	4.780e−04
stop	1.512e−01	1.520e−01	1.508e−01	8.522e−04	7.024e−04	5.495e−04
stop-retract	1.509e−01	1.516e−01	1.503e−01	5.753e−04	4.679e−04	6.179e−04
super-stop	1.511e−01	1.515e−01	1.496e−01	6.079e−04	4.934e−04	5.822e−04
super-zero-g	1.516e−01	1.512e−01	1.493e−01	6.439e−04	5.388e−04	7.108e−04
zero-g	1.521e−01	1.516e−01	1.497e−01	7.989e−04	6.975e−04	7.158e−04

Table 52: Measured contact velocity for collisions planned at velocity 0.25 m/s.

	mean [m/s]			standard deviation [m/s]		
reflex	hard	medium	soft	hard	medium	soft
admittance	2.548e−01	2.544e−01	2.519e−01	8.663e−04	8.086e−04	1.387e−03
admittance-stop	2.541e−01	2.526e−01	2.515e−01	6.439e−04	9.941e−04	1.082e−03
cart-retraction	2.533e−01	2.516e−01	2.512e−01	1.016e−03	1.288e−03	1.219e−03
joint-retraction	2.547e−01	2.534e−01	2.520e−01	9.979e−04	1.362e−03	7.807e−04
stop	2.562e−01	2.529e−01	2.470e−01	7.484e−04	7.951e−04	8.815e−04
stop-retract	2.535e−01	2.536e−01	2.519e−01	8.134e−04	1.269e−03	9.969e−04
super-stop	2.538e−01	2.509e−01	2.517e−01	1.469e−03	1.402e−03	6.065e−04
super-zero-g	2.559e−01	2.547e−01	2.536e−01	1.169e−03	1.585e−03	5.796e−04
zero-g	2.546e−01	2.538e−01	2.512e−01	6.726e−04	1.061e−03	1.331e−03

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