

Determining push-off forces in speed skating imitation drills

Dominik Krumm¹, Nicolas Kuske², Maja Neubert¹, Jens Buder¹, Fred Hamker² and Stephan Odenwald¹

¹ Sports Equipment and Technology, Chemnitz University of Technology, 09107 Chemnitz, Germany

² Professorship of Artificial Intelligence, Chemnitz University of Technology, 09107 Chemnitz, Germany

Architecture of the neural network

A neural network contains artificial neurons. Each neuron is a computational unit which gets one or multiple numbers as input and puts out one number. The artificial neural network known as perceptron contains one input layer and one output layer of neurons [1]. The input layer gets values from the environment. In our case the 16 voltage values from both pressure sensor insoles. Each neuron in this input layer is connected to at least one neuron of the output layer. This connection is known as weight and represented by a number. Each neuron in the output layer is implemented as an arbitrary function of the values which are forwarded to it. This function is known as an activation function [2]. The input to this function $f(y)$ is the scalar product of the weight vector w and the input vector x plus a bias term b . The mathematical notation is given in Equation 1, where the sum counts over all neurons in the input layer.

$$f(y) = f(wx + b) = f(\sum w_i x_i + b) \quad \text{Eq (1)}$$

We trained a deep neural network. A deep neural network (DNN) or multilayer perceptron contains at least one layer of neurons in between the input layer and the output layer. These additional layers are known as hidden layers. The first layer of the DNN is identical to the first layer of the perceptron. It forwards its input values to the neurons in the second layer of the DNN, which is the first hidden layer. Each layer gets input from all neurons in the layer before. We tested the performance of our DNN with one, two, three, four and five hidden layers. All hidden layers contained the same number of neurons, which we varied from 20 to 40, up to 60 units. The (unhidden) output layer contained only one neuron which was a linear function of all outputs of the last hidden layer. The mathematical notation of the output function of a neural network with one hidden layer is given in Equation 2. In this equation $f(y)$ is a vector function representing the output of all neurons of the first hidden layer. All single neurons from this layer, as well as their weights to the output layer and the bias are denoted by a subscript 1. The subscript 0 represents all neurons, weights and the biases from the input layer to each neuron of the hidden layer of the network. The linear function of the output layer is denoted with a g .

$$g(f(y)) = wf(y) + b_1 = \sum w_{k1} f_{k1} (\sum w_{ki0} x_{i0} + b_{k0}) + b_1 \quad \text{Eq (2)}$$

During training of our network, we compared two common activation functions. One was the rectified linear unit ReLU, which is zero until a threshold is reached after which it becomes a linear function of the input [3]. The other one was a simple sigmoid function. All neurons in the hidden layers were either ReLU or sigmoid units. We also varied the size of the batch of datapoints used for each training step as well as the number of training steps or epochs. All of these hyperparameters, to which one also counts the number of layers and neurons per layer as well as their activation function were not derived by the training algorithm but have been systematically varied to find

their optimal values. Only the weights and the biases are free parameters which are optimized during the training process.

The network was trained to minimize the loss function given by the mean squared error MSE , or difference, between each point of the force-time curve t_i and the model output g_i .

$$MSE = \frac{1}{m} (\sum t_i - g_i)^2 \quad \text{Eq (3)}$$

To find the minimum of the of the MSE in the high-dimensional weight (and bias) space we used the method of gradient descent [2][4]. Given a convex shape of the MSE manifold, differentiation with respect to the weights and biases results in a tangential vector which points in the direction of the manifold's minimum. The weights are incrementally changed into this direction, the next differentiation process takes place and so on, until a stop criterion is reached. The size of this incremental change is defined by the learning rate η . This update process of the weight (and bias, not shown) vector is presented in mathematical notation in Equation 4.

$$w(i + 1) = w(i) - \eta \nabla_w MSE(i) \quad \text{Eq (4)}$$

We used a stochastic gradient descent algorithm. That means instead of the complete data set, random subsamples, also known as batches, were used one at a time to compute the weight update. Each batch training is called one training epoch i . We stopped training after a certain number of epochs was reached. In the later epochs the values of the weights and biases gets closer to the minimal MSE . In order not to oscillate around this optimal point in parameter space, the learning rate was a decreasing function of the number of training epochs $\eta(i)$. This is also known as gradient descent decay [2]. Furthermore, we added a momentum term v to the gradient, which is itself a sum of the direction of past gradients. How far this sum reaches into the past is defined by its update factor μ . Equipped with this kind of short-term memory the algorithm becomes less disturbed by local noise in the shape of the manifold on his way to the global minimum. Following the idea of Nesterov, this memory momentum term was also added to the current position of the weight vector when computing the gradient to further stabilize the convergence of the algorithm [5][6]. The mathematical notation of the final weight parameter update algorithm is given by Equation 5 and Equation 6.

$$v(i + 1) = \mu v(i) - \eta(i) \nabla_w MSE(i, w + \mu v) \quad \text{Eq (5)}$$

$$w(i + 1) = w(i) + v(i + 1) \quad \text{Eq (6)}$$

After a systematic check of the optimal combination of hyperparameters as described above, we settled for the following algorithmic training values and DNN architecture:

Beginning learning rate η : 0.1

Decay rate: 10^{-6}

Momentum memory μ : 0.9

Activation function $f(y)$: ReLU

Number of hidden layers: 1

Neurons per hidden layer: 20

With 16 neurons in the input layer and one neuron (with a linear activation function) in the output layer as well as

all-to-all connections between layers (input- to hidden layer: 320 weights and 20 biases; hidden- to output layer: 20 weights and one bias) this leaves 361 trainable weight and bias parameters. We do not present the results of the DNN training procedure.

Architecture of the linear model

A multiple linear regression model is equivalent to a perceptron with a linear activation function of the neuron in the output layer. The model can be mathematically described by Equation 1. For clarity we rewrite it in a simpler form in Equation 7.

$$y = w_1x_1 + w_2x_2 + \dots + w_{16}x_{16} + b \quad \text{Eq (7)}$$

Each x_k represents the value of one insole pressure sensor. These values are known as independent variables or predictors [7]. The y is the dependent variable. The w_k are the coefficients which determine the predictive quality of each independent variable. The bias term b defines the value of the dependent variable if all predictors are zero and is also known as the intercept.

Again equivalent to the neural network approach presented above, we try to find the values of the coefficients and the bias term which minimize the mean squared error MSE , or difference, between each point of the force-time curve t_i and the model output y_i as denoted in Equation 8.

$$MSE = \frac{1}{m} (\sum t_i - y_i)^2 \quad \text{Eq (8)}$$

While gradient descent can be used to find this minimum, when y is a linear function the equation can be minimized using matrix algebra (QR decomposition) and iteratively reweighting the coefficients according to the new MSE until a stop criterion is reached. We will not go into the mathematical details but refer the interested reader to [8], for example.

The linear model does not include any hyperparameters and leaves us with 16 coefficients and one bias term as free parameters. We did not check normality of data distribution, equality of variance or homoscedasticity. This compromises the reliability of the p-values of our models. Consequently, we only excluded predictors with a p-value greater 0.5. All remaining statistical parameters of the 21 models fitted are given in the tables S5 to S25.

Data partitioning scheme for both models

Each participant was modelled separately. All models were trained using the concatenated data of the 16 insole pressure sensors collected during the first six trials on the slide board on the first of the participant's two measurement days. The ankle acceleration sensors did not substantially improve the models and were excluded from training. To use only data from the regular movement execution on the slide board, the data before the second sliding stroke and the data after the penultimate sliding stroke were truncated for each trial. Altogether, this data cleaning left about 13 seconds of recorded data per trial. With six trials at a measurement rate of 100 Hz this resulted on average in 7800 times 16 sensor values, giving 124,800 data points for the training of the skate model of each participant. Since the left and right push-off model are only trained with the data from bar contact to the

maximal push-off force for their respective side they are trained with about 2000 times 16 sensor values. This results in 32,000 data points for the training of each push-off model.

The accuracy of our models was tested on the four remaining trials of the first measurement day. This meant that 60% of data was used for training and 40% for testing on that day. We did not use additional data for validation, but utilised all ten trials of the second measurement day for testing generalisability over time.

References

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Tables

Table S1. Experience level description.

Experience level	Description
1	Participant is new to slide board imitation exercise and has no experience in speed skating itself other than activities such as public ice skating; participant may have basic skills in similar activities such as inline skating.
2	Participant is familiar with the slide board imitation exercise itself and has a history as an active athlete specifically in speed skating, although no more than five years.
3	Participant is an active athlete in speed skating, competing in national and international competitions; the slide board imitation exercise is standard use in their training schedule.
4	Participant is active at an international, professional and competitive level; the slide board imitation exercise can be mastered at his highest level of training.

Table S2. Force at bar contact (F_{BC}). Given are the means and standard deviations of the measured target variables derived from the force plates, the modelled variables predicted from the pressure input variables of the test data, and their relative differences (Δ); (a) F_{BC} independent of participant (p), day, trial and leg; (b) F_{BC} independent of participant, day and trial; (c) F_{BC} independent of participant, trial and leg; (d) F_{BC} independent of day, trial and leg.

		F_{BC} (N)		
		measured	modelled	Δ (%)
(a)	total	711 ± 243	547 ± 171	17.7 ± 32.0
(b)	left leg	640 ± 161	556 ± 197	9.3 ± 38.3
	right leg	779 ± 286	538 ± 141	25.8 ± 21.5
(c)	day 1	709 ± 261	514 ± 145	23.4 ± 19.7
	day 2	711 ± 238	561 ± 180	15.2 ± 35.7
(d)	p #1	478 ± 116	396 ± 63	12.6 ± 24.2
	p #2	651 ± 111	519 ± 69	18.5 ± 14.4
	p #3	492 ± 113	499 ± 235	-6.8 ± 59.6
	p #4	995 ± 218	564 ± 109	40.8 ± 18.3
	p #5	802 ± 176	597 ± 120	22.4 ± 23.0
	p #6	982 ± 210	809 ± 131	13.2 ± 26.2
	p #7	665 ± 106	489 ± 82	25.0 ± 16.2

Table S3. Force at push-off initial (F_{POi}). Given are the means and standard deviations of the measured target variables derived from the force plates, the modelled variables predicted from the pressure input variables of the test data, and their relative differences (Δ); (a) F_{POi} independent of participant (p), day, trial and leg; (b) F_{POi} independent of participant, day and trial; (c) F_{POi} independent of participant, trial and leg; (d) F_{POi} independent of day, trial and leg.

		F_{POi} (N)		
		measured	modelled	Δ (%)
(a)	total	254 $\pm$ 108	274 $\pm$ 110	-378.1 $\pm$ 9988.8
(b)	left leg	239 $\pm$ 98	270 $\pm$ 95	-21.8 $\pm$ 54.4
	right leg	250 $\pm$ 117	277 $\pm$ 123	-726.2 $\pm$ 14044.8
(c)	day 1	239 $\pm$ 112	257 $\pm$ 114	-1229.1 $\pm$ 18392.6
	day 2	247 $\pm$ 104	281 $\pm$ 107	-22.1 $\pm$ 48.9
(d)	p #1	257 $\pm$ 70	266 $\pm$ 69	-7.1 $\pm$ 29.0
	p #2	194 $\pm$ 38	246 $\pm$ 61	-28.2 $\pm$ 30.3
	p #3	88 $\pm$ 27	117 $\pm$ 61	-2586.4 $\pm$ 26598.5
	p #4	373 $\pm$ 71	392 $\pm$ 64	-6.9 $\pm$ 15.9
	p #5	281 $\pm$ 61	319 $\pm$ 85	-15.3 $\pm$ 27.9
	p #6	375 $\pm$ 66	363 $\pm$ 110	2.4 $\pm$ 27.5
	p #7	191 $\pm$ 36	247 $\pm$ 53	-31.8 $\pm$ 30.2

Table S4. Force at bar off (F_{BO}). Given are the means and standard deviations of the measured target variables derived from the force plates, the modelled variables predicted from the pressure input variables of the test data, and their relative differences (Δ); (a) F_{BO} independent of participant (p), day, trial and leg; (b) F_{BO} independent of participant, day and trial; (c) F_{BO} independent of participant, trial and leg; (d) F_{BO} independent of day, trial and leg.

		F_{BO} (N)		
		measured	modelled	Δ (%)
(a)	total	111 $\pm$ 24	171 $\pm$ 97	-67.2 $\pm$ 223.6
(b)	left leg	117 $\pm$ 23	186 $\pm$ 121	-63.8 $\pm$ 132.2
	right leg	105 $\pm$ 23	157 $\pm$ 62	-70.5 $\pm$ 286.1
(c)	day 1	112 $\pm$ 24	152 $\pm$ 55	-48.9 $\pm$ 133.4
	day 2	110 $\pm$ 24	179 $\pm$ 108	-74.9 $\pm$ 251.6
(d)	p #1	129 $\pm$ 17	181 $\pm$ 40	-42.3 $\pm$ 35.5
	p #2	114 $\pm$ 28	158 $\pm$ 42	-43.6 $\pm$ 39.1
	p #3	115 $\pm$ 12	77 $\pm$ 38	32.7 $\pm$ 34.8
	p #4	114 $\pm$ 10	172 $\pm$ 71	-49.9 $\pm$ 59.5
	p #5	98 $\pm$ 33	180 $\pm$ 59	-152.4 $\pm$ 532.1
	p #6	102 $\pm$ 26	266 $\pm$ 188	-135.9 $\pm$ 130.1
	p #7	104 $\pm$ 19	173 $\pm$ 56	-85.8 $\pm$ 169.5

Tables of model parameters

The model parameters for the skate model (AM), the left push-off model (lM) and the right push-off model (rM) are given below. In all following tables AML_k is the coefficient of the k-th insole pressure sensor in the left shoe. Similar for the right shoe with AMR_k. SE is the standard error and tStat the t-value from which the probability (pValue) for a false positive was derived. The coefficient of determination R-squared denotes the fraction of variance which is explained by the model.

Table S5. Skate model parameters for participant 1.

	Estimate	SE	tStat	pValue
(Intercept)	116.5	8.2	14.2	0.0
AML1	-13.4	15.7	-0.9	0.4
AML2	-114.3	9.3	-12.3	0.0
AML3	-121.0	14.0	-8.6	0.0
AML4	-130.7	14.6	-9.0	0.0
AML5	-102.5	8.6	-12.0	0.0
AML6	-310.7	8.0	-38.7	0.0
AML7	-167.9	17.5	-9.6	0.0
AML8	-288.1	16.0	-18.0	0.0
AMR1	-28.1	11.7	-2.4	0.0
AMR2	79.1	9.0	8.8	0.0
AMR3	201.0	10.6	19.0	0.0
AMR4	-83.6	14.1	-5.9	0.0
AMR5	85.4	14.4	5.9	0.0
AMR6	144.4	8.3	17.3	0.0
AMR7	101.3	13.1	7.7	0.0
AMR8	75.3	16.8	4.5	0.0

Number of observations: 6607, Error degrees of freedom: 6590; Root Mean Squared Error: 98.3; R-squared: 0.9;
F-statistic vs. constant model: 2.9e+03, p-value = 0

Table S6. Left push-off model parameters for participant 1.

	Estimate	SE	tStat	pValue
(Intercept)	-58.2	19.3	-3.0	0.0
lML1	99.9	19.1	5.2	0.0
lML2	103.2	16.4	6.3	0.0
lML3	153.3	17.1	9.0	0.0
lML5	-47.2	12.1	-3.9	0.0
lML6	372.2	10.3	36.0	0.0
lML8	213.1	20.3	10.5	0.0
lMR1	97.6	90.3	1.1	0.3
lMR2	302.4	31.5	9.6	0.0
lMR3	-101.5	48.9	-2.1	0.0
lMR4	-134.5	41.6	-3.2	0.0
lMR6	148.7	18.3	8.1	0.0
lMR7	91.7	43.3	2.1	0.0
lMR8	-199.1	114.5	-1.7	0.1

Number of observations: 2006, Error degrees of freedom: 1992; Root Mean Squared Error: 76.9; R-squared: 0.6;
F-statistic vs. constant model: 165, p-value = 0

Table S7. Right push-off model parameters for participant 1.

	Estimate	SE	tStat	pValue
(Intercept)	129.9	15.7	8.3	0.0
rML1	-198.5	65.4	-3.0	0.0
rML2	312.2	46.5	6.7	0.0
rML3	-777.6	78.9	-9.9	0.0
rML4	-492.0	104.9	-4.7	0.0
rML5	61.0	35.0	1.7	0.1
rML6	72.2	30.5	2.4	0.0
rML7	291.6	44.4	6.6	0.0
rML8	-251.1	225.3	-1.1	0.3
rMR1	53.4	13.1	4.1	0.0
rMR2	-78.6	13.1	-6.0	0.0
rMR3	275.1	14.5	18.9	0.0
rMR4	-24.7	17.1	-1.4	0.2
rMR5	-103.9	25.0	-4.2	0.0
rMR6	265.5	12.6	21.0	0.0
rMR7	63.6	17.5	3.6	0.0
rMR8	71.0	21.5	3.3	0.0

Number of observations: 1582, Error degrees of freedom: 1565; Root Mean Squared Error: 76; R-squared: 0.6;
F-statistic vs. constant model: 123, p-value = 3.3e-263

Table S8. Skate model parameters for participant 2.

	Estimate	SE	tStat	pValue
(Intercept)	-20.1	6.6	-3.1	0.0
AML1	73.4	26.2	2.8	0.0
AML2	-378.8	17.7	-21.4	0.0
AML3	-82.1	14.5	-5.7	0.0
AML4	120.9	17.8	6.8	0.0
AML5	-106.9	14.8	-7.2	0.0
AML6	-200.6	16.1	-12.4	0.0
AML7	-78.7	23.0	-3.4	0.0
AML8	-124.3	30.6	-4.1	0.0
AMR1	58.0	19.2	3.0	0.0
AMR2	288.9	15.7	18.4	0.0
AMR3	143.8	14.4	10.0	0.0
AMR5	132.0	14.2	9.3	0.0
AMR6	138.0	11.8	11.7	0.0
AMR8	252.1	23.2	10.9	0.0

Number of observations: 6039, Error degrees of freedom: 6024; Root Mean Squared Error: 90.6; R-squared: 0.9;
F-statistic vs. constant model: 3.4e+03, p-value = 0

Table S9. Left push-off model parameters for participant 2.

	Estimate	SE	tStat	pValue
(Intercept)	-186.9	13.9	-13.4	0.0
IML1	-286.0	46.4	-6.2	0.0
IML2	780.6	38.3	20.4	0.0
IML3	81.5	22.4	3.7	0.0
IML4	-78.8	25.8	-3.1	0.0
IML5	-67.3	19.2	-3.5	0.0
IML6	461.6	25.0	18.5	0.0
IML7	-60.9	26.2	-2.3	0.0
IML8	468.9	33.7	13.9	0.0
IMR1	178.8	251.4	0.7	0.5
IMR2	272.7	129.0	2.1	0.0
IMR3	-221.3	54.5	-4.1	0.0
IMR4	-1055.6	184.8	-5.7	0.0
IMR5	-114.0	75.6	-1.5	0.1
IMR6	217.9	26.2	8.3	0.0
IMR7	136.6	70.6	1.9	0.1
IMR8	-82.2	85.3	-1.0	0.3

Number of observations: 1581, Error degrees of freedom: 1564; Root Mean Squared Error: 64.5; R-squared: 0.7;
F-statistic vs. constant model: 261, p-value = 0

Table S10. Right push-off model parameters for participant 2.

	Estimate	SE	tStat	pValue
(Intercept)	70.7	10.2	6.9	0.0
rML1	714.5	272.6	2.6	0.0
rML2	-237.2	268.4	-0.9	0.4
rML3	-200.5	71.9	-2.8	0.0
rML4	137.3	142.4	1.0	0.3
rML5	-22.5	29.4	-0.8	0.4
rML6	65.4	31.2	2.1	0.0
rML7	373.4	108.2	3.5	0.0
rML8	-231.9	148.0	-1.6	0.1
rMR1	-186.8	27.5	-6.8	0.0
rMR2	228.1	22.4	10.2	0.0
rMR3	111.3	19.8	5.6	0.0
rMR4	239.2	18.6	12.9	0.0
rMR5	-52.9	19.1	-2.8	0.0
rMR6	185.3	18.1	10.2	0.0
rMR7	93.5	18.2	5.2	0.0
rMR8	161.7	23.6	6.9	0.0

Number of observations: 1633, Error degrees of freedom: 1616; Root Mean Squared Error: 67.7; R-squared: 0.7;
 F-statistic vs. constant model: 219, p-value = 0

Table S11. Skate model parameters for participant 3.

	Estimate	SE	tStat	pValue
(Intercept)	18.8	7.1	2.7	0.0
AML1	175.7	14.7	12.0	0.0
AML2	-379.0	9.3	-40.6	0.0
AML3	80.0	9.6	8.3	0.0
AML4	50.0	9.9	5.1	0.0
AML5	-214.4	12.9	-16.6	0.0
AML6	-51.2	9.9	-5.2	0.0
AML7	-37.8	13.8	-2.7	0.0
AML8	-115.1	10.3	-11.2	0.0
AMR1	-304.6	8.7	-35.0	0.0
AMR2	404.6	6.5	62.7	0.0
AMR3	-108.6	11.5	-9.5	0.0
AMR4	-150.2	10.2	-14.7	0.0
AMR5	25.8	12.5	2.1	0.0
AMR6	98.8	5.6	17.8	0.0
AMR7	-129.0	10.1	-12.8	0.0
AMR8	179.0	10.7	16.8	0.0

Number of observations: 11047, Error degrees of freedom: 11030; Root Mean Squared Error: 85.3; R-squared: 0.8;
 F-statistic vs. constant model: 2.9e+03, p-value = 0

Table S12. Left push-off model parameters for participant 3.

	Estimate	SE	tStat	pValue
(Intercept)	-195.4	17.3	-11.3	0.0
lML1	-52.4	15.4	-3.4	0.0
lML2	278.7	10.5	26.6	0.0
lML3	69.3	12.4	5.6	0.0
lML4	-18.0	10.3	-1.7	0.1
lML5	-30.7	16.6	-1.9	0.1
lML6	211.7	15.4	13.8	0.0
lML7	261.2	23.5	11.1	0.0
lML8	59.9	13.0	4.6	0.0
lMR2	826.0	70.0	11.8	0.0
lMR4	81.0	40.8	2.0	0.1
lMR5	-138.0	40.3	-3.4	0.0
lMR6	27.2	9.2	3.0	0.0
lMR7	329.2	18.4	17.9	0.0
lMR8	529.5	58.8	9.0	0.0

Number of observations: 3589, Error degrees of freedom: 3574; Root Mean Squared Error: 60.8; R-squared: 0.7;
F-statistic vs. constant model: 623, p-value = 0

Table S13. Right push-off model parameters for participant 3.

	Estimate	SE	tStat	pValue
(Intercept)	-129.2	11.4	-11.3	0.0
rML1	1287.8	92.0	14.0	0.0
rML2	-62.2	50.1	-1.2	0.2
rML3	51.5	21.3	2.4	0.0
rML4	125.5	18.2	6.9	0.0
rML5	147.8	56.5	2.6	0.0
rML6	135.8	11.8	11.6	0.0
rML7	65.7	21.1	3.1	0.0
rML8	165.3	54.5	3.0	0.0
rMR1	-87.0	8.9	-9.8	0.0
rMR2	280.6	10.3	27.3	0.0
rMR3	22.2	13.2	1.7	0.1
rMR4	-98.4	9.8	-10.1	0.0
rMR5	-69.3	13.7	-5.1	0.0
rMR6	146.1	7.2	20.3	0.0
rMR7	157.0	14.4	10.9	0.0
rMR8	51.6	12.4	4.2	0.0

Number of observations: 3855, Error degrees of freedom: 3838; Root Mean Squared Error: 55.5; R-squared: 0.8;
F-statistic vs. constant model: 806, p-value = 0

Table S14. Skate model parameters for participant 4.

	Estimate	SE	tStat	pValue
(Intercept)	59.0	51.2	1.2	0.3
AML1	-472.5	25.4	-18.6	0.0
AML2	111.5	27.4	4.1	0.0
AML4	-233.7	31.3	-7.5	0.0
AML5	-36.5	52.8	-0.7	0.5
AML6	-454.0	27.1	-16.8	0.0
AML7	-387.7	32.8	-11.8	0.0
AML8	-45.3	35.2	-1.3	0.2
AMR1	76.0	26.0	2.9	0.0
AMR2	-105.7	30.4	-3.5	0.0
AMR3	44.0	23.9	1.8	0.1
AMR4	211.0	24.6	8.6	0.0
AMR5	154.4	25.5	6.1	0.0
AMR6	301.5	19.4	15.5	0.0
AMR7	174.2	36.5	4.8	0.0
AMR8	197.6	30.3	6.5	0.0

Number of observations: 4167, Error degrees of freedom: 4151; Root Mean Squared Error: 148; R-squared: 0.9;

F-statistic vs. constant model: 2e+03, p-value = 0

Table S15. Left push-off model parameters for participant 4.

	Estimate	SE	tStat	pValue
(Intercept)	278.3	71.5	3.9	0.0
IML1	92.1	31.7	2.9	0.0
IML2	-135.9	21.5	-6.3	0.0
IML4	101.9	32.4	3.1	0.0
IML5	-245.8	47.7	-5.2	0.0
IML6	-119.6	34.5	-3.5	0.0
IML7	-157.1	39.3	-4.0	0.0
IMR1	-230.9	37.5	-6.2	0.0
IMR4	44.0	32.5	1.4	0.2
IMR5	159.9	92.2	1.7	0.1
IMR6	114.0	26.9	4.2	0.0
IMR7	924.5	68.2	13.6	0.0

Number of observations: 1306, Error degrees of freedom: 1294; Root Mean Squared Error: 95.6; R-squared: 0.3;

F-statistic vs. constant model: 29.1, p-value = 4.8e-75

Table S16. Right push-off model parameters for participant 4.

	Estimate	SE	tStat	pValue
(Intercept)	792.6	162.7	4.9	0.0
rML4	-216.4	92.3	-2.3	0.0
rML5	773.2	484.9	1.6	0.1
rML6	-569.8	135.6	-4.2	0.0
rML7	275.7	81.0	3.4	0.0
rMR1	-285.2	73.2	-3.9	0.0
rMR2	-223.0	45.9	-4.9	0.0
rMR3	-18.9	22.7	-0.8	0.4
rMR4	211.8	51.4	4.1	0.0
rMR5	-76.5	29.5	-2.6	0.0
rMR6	-101.0	41.6	-2.4	0.0
rMR7	-244.3	74.2	-3.3	0.0
rMR8	-124.5	62.7	-2.0	0.1

Number of observations: 1318, Error degrees of freedom: 1305; Root Mean Squared Error: 120; R-squared: 0.2;
F-statistic vs. constant model: 22.7, p-value = 7.3e-59

Table S17. Skate model parameters for participant 5.

	Estimate	SE	tStat	pValue
(Intercept)	4.8	10.2	0.5	0.6
AML2	-438.5	19.9	-22.1	0.0
AML3	26.0	14.0	1.9	0.1
AML4	-137.7	23.9	-5.8	0.0
AML5	-83.9	17.9	-4.7	0.0
AML6	-90.4	20.1	-4.5	0.0
AML7	208.5	26.4	7.9	0.0
AML8	-454.7	26.1	-17.4	0.0
AMR1	130.1	19.1	6.8	0.0
AMR2	156.4	16.5	9.5	0.0
AMR3	181.6	14.7	12.4	0.0
AMR4	-225.6	28.2	-8.0	0.0
AMR5	132.9	20.7	6.4	0.0
AMR6	66.5	12.7	5.2	0.0
AMR7	110.1	19.8	5.6	0.0
AMR8	219.1	21.7	10.1	0.0

Number of observations: 5542, Error degrees of freedom: 5526; Root Mean Squared Error: 142; R-squared: 0.8;
F-statistic vs. constant model: 1.4e+03, p-value = 0

Table S18. Left push-off model parameters for participant 5.

	Estimate	SE	tStat	pValue
(Intercept)	-74.6	52.7	-1.4	0.2
lML1	211.4	35.7	5.9	0.0
lML2	241.7	31.3	7.7	0.0
lML3	111.0	21.3	5.2	0.0
lML4	96.8	34.2	2.8	0.0
lML6	155.7	41.9	3.7	0.0
lML7	-249.9	39.2	-6.4	0.0
lML8	462.9	33.3	13.9	0.0
lMR3	-386.4	302.8	-1.3	0.2
lMR4	856.9	170.3	5.0	0.0
lMR5	-159.2	85.7	-1.9	0.1
lMR6	173.9	31.8	5.5	0.0
lMR8	252.3	103.8	2.4	0.0

Number of observations: 1650, Error degrees of freedom: 1637; Root Mean Squared Error: 129; R-squared: 0.4;
F-statistic vs. constant model: 62.5, p-value = 2.5e-156

Table S19. Right push-off model parameters for participant 5.

	Estimate	SE	tStat	pValue
(Intercept)	-128.9	20.9	-6.2	0.0
rML1	656.0	77.4	8.5	0.0
rML2	999.6	171.3	5.8	0.0
rML3	99.9	49.2	2.0	0.0
rML4	-368.7	143.7	-2.6	0.0
rML5	-180.4	58.8	-3.1	0.0
rML6	661.7	39.4	16.8	0.0
rML7	126.9	67.2	1.9	0.1
rML8	-229.3	86.4	-2.7	0.0
rMR1	114.6	20.5	5.6	0.0
rMR2	-42.4	20.6	-2.1	0.0
rMR3	262.0	18.3	14.3	0.0
rMR4	37.7	36.2	1.0	0.3
rMR5	-37.9	28.2	-1.3	0.2
rMR6	357.0	26.3	13.6	0.0
rMR7	173.5	28.6	6.1	0.0
rMR8	182.3	27.6	6.6	0.0

Number of observations: 1764, Error degrees of freedom: 1747; Root Mean Squared Error: 121; R-squared: 0.5;
F-statistic vs. constant model: 94, p-value = 9.6e-222

Table S20. Skate model parameters for participant 6.

	Estimate	SE	tStat	pValue
(Intercept)	186.9	12.7	14.7	0.0
AML1	-652.1	27.0	-24.2	0.0
AML2	-199.8	40.6	-4.9	0.0
AML3	-258.5	27.5	-9.4	0.0
AML5	-163.2	58.6	-2.8	0.0
AML6	-244.5	18.0	-13.6	0.0
AML7	-274.4	32.6	-8.4	0.0
AML8	-307.3	24.7	-12.5	0.0
AMR1	-43.7	16.0	-2.7	0.0
AMR2	186.0	23.7	7.9	0.0
AMR3	1445.9	370.7	3.9	0.0
AMR4	75.9	67.8	1.1	0.3
AMR5	147.6	54.1	2.7	0.0
AMR6	159.1	10.4	15.3	0.0
AMR7	105.8	19.5	5.4	0.0
AMR8	484.9	19.5	24.9	0.0

Number of observations: 3494, Error degrees of freedom: 3478; Root Mean Squared Error: 113; R-squared: 0.9;
F-statistic vs. constant model: 1.9e+03, p-value = 0

Table S21. Left push-off model parameters for participant 6.

	Estimate	SE	tStat	pValue
(Intercept)	-477.0	74.2	-6.4	0.0
IML1	1003.0	45.9	21.8	0.0
IML2	154.6	50.1	3.1	0.0
IML3	169.7	48.3	3.5	0.0
IML4	-186.2	106.6	-1.8	0.1
IML5	254.8	84.3	3.0	0.0
IML6	408.5	29.9	13.7	0.0
IML7	778.3	62.6	12.4	0.0
IML8	204.4	42.4	4.8	0.0
IMR1	36.5	47.2	0.8	0.4
IMR2	109.1	59.3	1.8	0.1
IMR4	156.8	150.6	1.0	0.3
IMR6	13594.3	16993.4	0.8	0.4
IMR7	329.8	79.2	4.2	0.0

Number of observations: 1049, Error degrees of freedom: 1035; Root Mean Squared Error: 96.7; R-squared: 0.5;
F-statistic vs. constant model: 61.4, p-value = 2e-137

Table S22. Right push-off model parameters for participant 6.

	Estimate	SE	tStat	pValue
(Intercept)	219.6	77.4	2.8	0.0
rML7	54.1	95.4	0.6	0.5
rMR1	-47.6	32.1	-1.5	0.1
rMR2	95.0	36.1	2.6	0.0
rMR4	109.7	103.2	1.1	0.3
rMR6	197.6	16.5	12.0	0.0
rMR7	88.0	32.8	2.7	0.0
rMR8	353.6	45.6	7.8	0.0

Number of observations: 929, Error degrees of freedom: 921; Root Mean Squared Error: 83.6; R-squared: 0.4;
F-statistic vs. constant model: 34.7, p-value = 6.9e-83

Table S23. Skate model parameters for participant 7.

	Estimate	SE	tStat	pValue
(Intercept)	42.5	10.5	4.1	0.0
AML1	52.1	31.1	1.7	0.1
AML2	-343.1	15.5	-22.2	0.0
AML3	-107.0	24.5	-4.4	0.0
AML4	-16.1	15.0	-1.1	0.3
AML5	-149.0	14.5	-10.3	0.0
AML6	-206.6	19.6	-10.5	0.0
AML8	-246.4	20.5	-12.0	0.0
AMR1	182.5	31.3	5.8	0.0
AMR3	310.5	14.5	21.5	0.0
AMR4	-39.8	14.8	-2.7	0.0
AMR5	331.8	25.3	13.1	0.0
AMR6	-40.3	12.5	-3.2	0.0
AMR7	-84.0	24.1	-3.5	0.0
AMR8	248.0	17.7	14.0	0.0

Number of observations: 4555, Error degrees of freedom: 4540; Root Mean Squared Error: 108; R-squared: 0.9;
F-statistic vs. constant model: 2e+03, p-value = 0

Table S24. Left push-off model parameters for participant 7.

	Estimate	SE	tStat	pValue
(Intercept)	71.2	40.2	1.8	0.1
lML1	158.5	38.3	4.1	0.0
lML3	279.6	33.6	8.3	0.0
lML4	37.0	16.8	2.2	0.0
lML5	77.7	17.6	4.4	0.0
lML6	253.2	27.0	9.4	0.0
lML7	289.2	40.5	7.1	0.0
lML8	25.6	22.1	1.2	0.3
lMR2	184.9	47.4	3.9	0.0
lMR3	312.8	90.0	3.5	0.0
lMR4	155.4	50.1	3.1	0.0
lMR5	-105.7	160.8	-0.7	0.5
lMR7	82.4	45.0	1.8	0.1

Number of observations: 1319, Error degrees of freedom: 1306; Root Mean Squared Error: 82.3; R-squared: 0.4;
F-statistic vs. constant model: 64.8, p-value = 7.1e-153

Table S25. Right push-off model parameters for participant 7.

	Estimate	SE	tStat	pValue
(Intercept)	110.4	34.1	3.2	0.0
rML2	-189.7	80.0	-2.4	0.0
rML3	191.9	56.2	3.4	0.0
rML4	203.5	63.7	3.2	0.0
rML5	52.6	86.5	0.6	0.5
rML6	-254.7	139.1	-1.8	0.1
rML7	561.6	138.5	4.1	0.0
rMR1	365.0	31.5	11.6	0.0
rMR2	-126.4	30.9	-4.1	0.0
rMR3	122.3	17.0	7.2	0.0
rMR4	135.3	20.6	6.6	0.0
rMR5	23.4	29.1	0.8	0.4
rMR6	137.3	16.1	8.5	0.0
rMR7	98.0	48.8	2.0	0.0
rMR8	246.5	21.8	11.3	0.0

Number of observations: 1459, Error degrees of freedom: 1444; Root Mean Squared Error: 81.3; R-squared: 0.5;
F-statistic vs. constant model: 81, p-value = 2.2e-187