A deep learning approach to predicting knee loading using 3D trajectories of anatomical landmarks

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Background

- Knee osteoarthritis (OA) is a leading cause of years lost to disability worldwide [1] and is accelerated by excessive mechanical loading.
- The knee adduction moment (KAM) is a measure of load estimated from using multi-body dynamics (Figure 1).
- Gait modifications reduce KAM and joint pain [2] but require a personalization visit to a gait lab with expensive motion capture cameras and forceplates.
- OpenPose identifies joint positions from images making it an inexpensive alternative to motion capture [3].

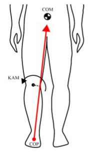

Figure 1: The knee adduction moment (KAM) is calculated using forces and limb positions/orientations.

Our goal is to predict the peak knee adduction moment using motion capture marker positions alone.

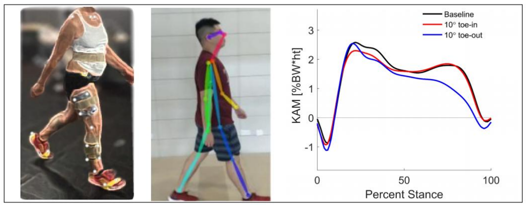

Figure 2. *Left:* Current means of calculating KAM requires motion capture and walking over force plates. *Middle*: Joint position identification using OpenPose [3]. *Right:* Gait modifications such as changing the foot angle reduce the knee adduction moment peaks.

Data

3D motion capture marker positions relative to the center of the PSIS markers during the first half of the gait cycle (8 times points) during varying gait modifications were used to predict peak KAM per step. This data was collected over the past 3 years for 98 people, giving a total of 125,415 steps.

- Input: 125,415 steps x 118 features x 8 timesteps
  Output: 125,415 steps x 1 (Peak KAM)

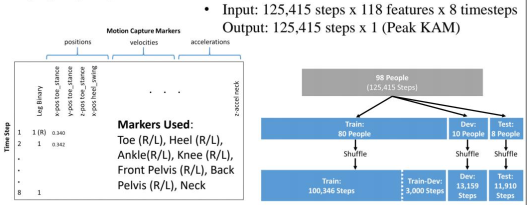

Figure 3: *Right:* Input matrix. *Left:* Data split.

Model

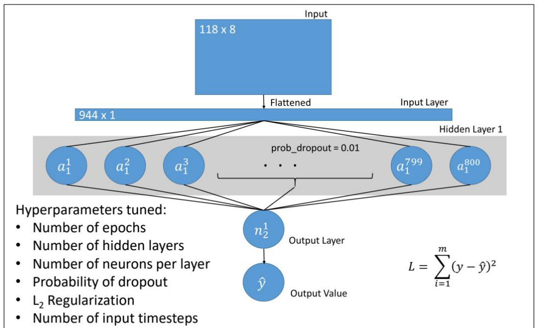

Figure 4: Diagram of best model (2-layer fully connected neural network)

Results

Table 1: Results of different models and input variations

Model	Details	Train r^2	Dev r^2	Test r^2	RMSE
CNN	3 Conv1D layers, 3 fully connected (FC) layers, 40 epochs	0.94	0.61	0.59	0.81
LSTM	2 LSTM layers, 1 FC layer, 40 epochs	0.84	0.54	0.56	0.82
Fully Connected	2 FC layers, 40 epochs (Positions, Velocities, Accelerations)	0.97	0.88	0.80	0.57
	Front View Only (Positions, Velocities, Accelerations)	0.95	0.87	0.78	0.60
	Side View Only (Positions, Velocities, Accelerations)	0.92	0.56	0.44	0.97
	Positions only	0.95	0.83	0.76	0.63
	Positions + Velocities only	0.96	0.88	0.81	0.56
	Positions + Accelerations only	0.96	0.86	0.77	0.62

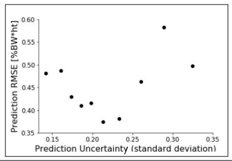

Figure 5: Prediction root mean squared error (RMSE) vs Prediction Uncertainty for 10 models which trained on 70% of the training set. Prediction uncertainty is estimated as the standard deviation of test set predictions from each of the 10 models. Each dot represents 10% of the training set sorted by standard deviation. Ideally, predictions with lower uncertainty would also have lower RMSE allowing predictive confidence for new examples.

Results

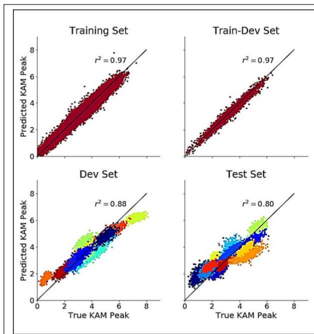

Figure 6: Predicted KAM vs. true KAM for all four data splits.

- Fully connected NN performed the best (Table 1)
- Using front view positions (y, z) only gave similar results to all positions (x, y, z), side view (x, z) only was less accurate (Table 1)
- Accuracy is higher if the model trained on the person's data before (train-dev) than if it had never trained on a person's data (test) (Figure 6)
- Lower model confidence corresponds with greater RMSE error (Figure 5)
- Saliency map shows higher sensitivity to knee, heel, and neck side-side and pelvis up-down positions (Figure 7)

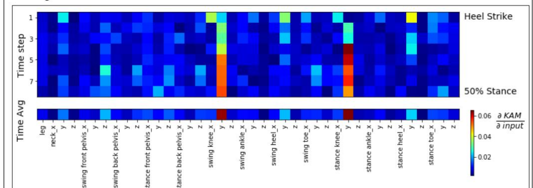

Figure 7: Saliency map showing which input changes cause the greatest change in output.

Conclusions

- Fully connected network predicts KAM peaks with $r^2 = 0.80$
- Predicting KAM most sensitive to knee and heel side-side positions
- Next step: predict KAM using video data and OpenPose

References and Acknowledgments

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1. Centers for Disease Control and Prevention, USA. 2009. Prevalence and most common causes of disability among adults - United States. MMWR Morb. Mortal. Wkly. Rep. 58, 421–426.
2. Shull, P.B., Shultz, R., Silder, A., Dragoo, J.L., Besier, T.F., Cutkosky, M.R., Delp, S.L., 2013a. Toe-in gait reduces the first peak knee adduction moment in patients with medial compartment knee osteoarthritis. J. Biomech. 46, 122–128.
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