# OpenSim Model Improvements to Support High Joint Angle Resistive Exercising

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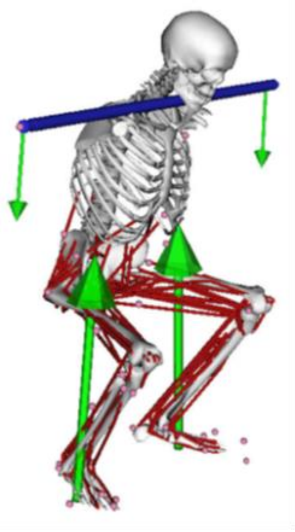
# NASA Digital Astronaut Program

- The Digital Astronaut Project implements well-vetted computational models to predict and assess spaceflight health and performance risks and enhance countermeasure development.
- The Digital Astronaut project is using OpenSim to analyze the following exercises:
  - Squat
  - Single-leg Squat
  - Heel Raise
  - Deadlift
- The OpenSim software developed at Stanford University is a freely available biomechanical simulation software which can be used to:
  - Develop models of musculoskeletal structures
  - Create dynamic simulations of exercise movements
  - Calculate estimates for muscle and joint loads

# Biomechanical Modeling with OpenSim

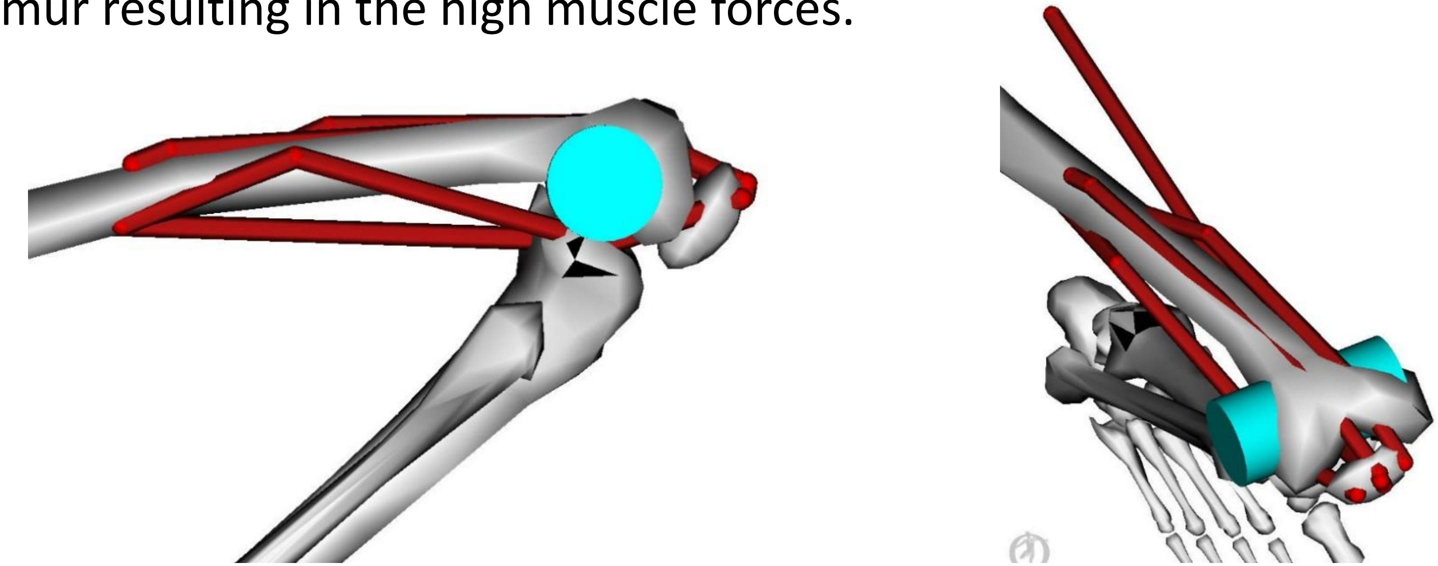
- The Digital Astronaut Project is using a modified version of the Arnold [1] OpenSim model to estimate muscle and joint forces and joint moments.
- The Arnold model includes updated data describing muscle architecture that relates fiber length and joint angle and has complex muscle wrapping surfaces for a wider range of hip and knee joint angles.
- The Digital Astronaut Project is evaluating exercises that involve performing squats sometimes at deep hip and knee angles greater than $90^o$.
- Initial analyses with the Arnold model resulted in high forces at the knee as the test subject neared the bottom of the squat.

1. Arnold, E.M., et al., A Model of the Lower Limb for Analysis of Human Movement, Annals of Biomedical Engineering, Vol. 38, No. 2, pp. 269–279, February, 2010.



# OpenSim Knee Joint Modeling

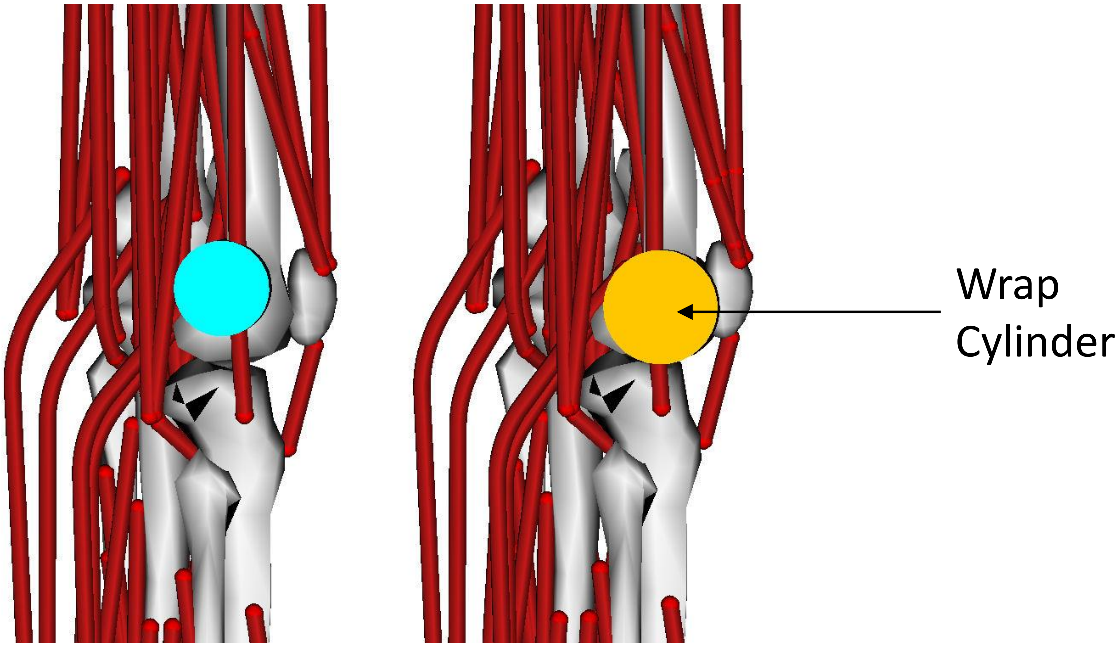
- After examination of the muscle forces calculated by OpenSim and the knee area during motion, it was discovered that the muscles were moving into the femur as the model neared the bottom of the squat.
- The Arnold model includes a cylinder at the knee joint called a wrap surface that guides the muscles around the knee during movement.
- The muscles were not wrapping around the top of this cylinder as expected and would jump to the bottom of the cylinder and into the femur resulting in the high muscle forces.



Knee Joint Before Modifications to the Wrap Surface and Muscle Path Points

# Knee Wrap Surface Modifications

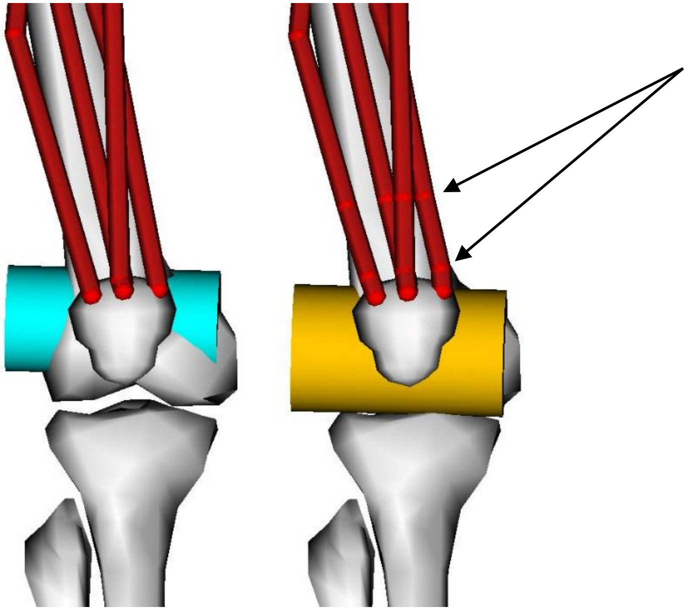
- The “KnExt at fem” cylindrical wrap surface attached to the shaft axis body at the knee in the OpenSim model was modified as shown below.
- The radius of the cylinder was increased from 2.5 cm to 3.0 cm.
- The wrap cylinder was translated distally by 1.49 cm.
- The wrap cylinder was translated anteriorly by 0.97 cm.



Original Modified

# Knee Muscle Path Point Modifications

- The muscles include path points that divide the muscle into segments.
- Path points were added to the four muscles at the knee listed below to allow more movement at the bottom of the squat.
- The first point was added approximately 1 cm proximally to the patella for the three Vastus muscles.
- The second point was added approximately 4 cm proximally to the patella for all four muscles.



Original Modified

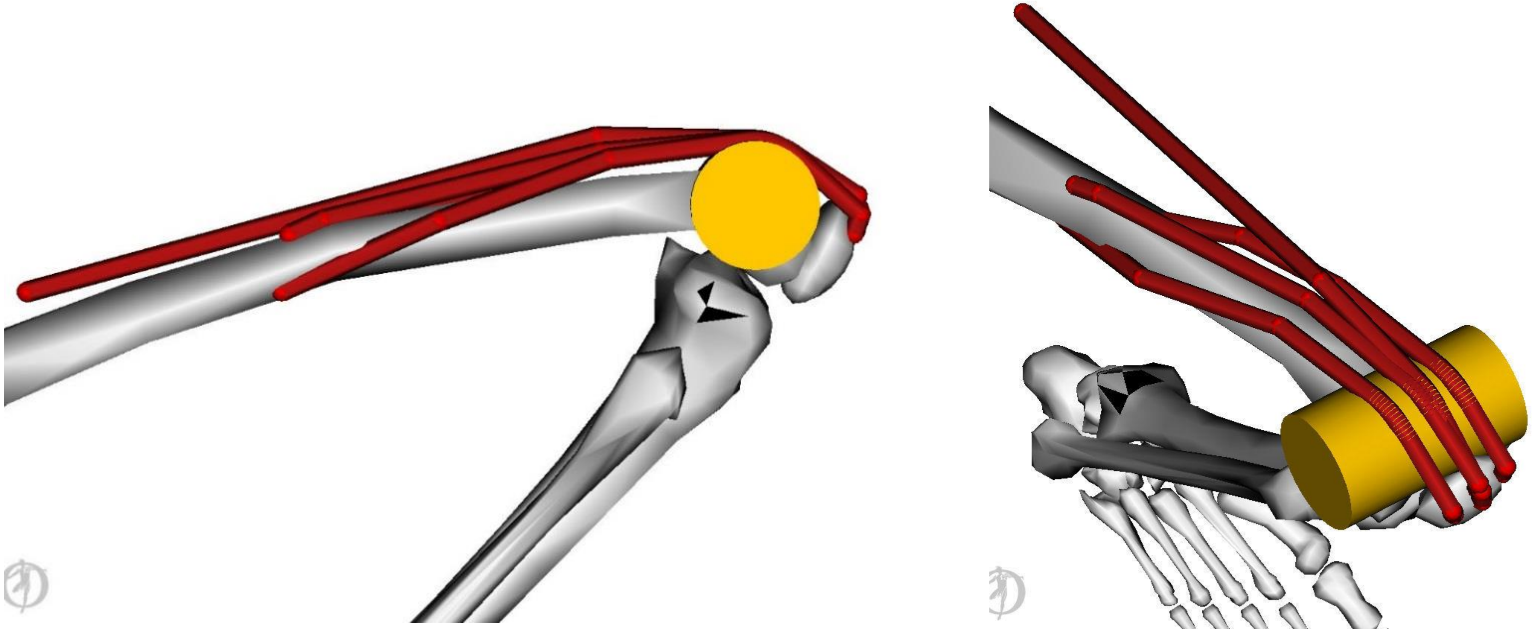
Additional path points added to the following muscles:

- Rectus Femoris
- Vastus Intermedius
- Vastus Lateralis
- Vastus Medialis

(other muscles are hidden)

# OpenSim Knee Joint Results

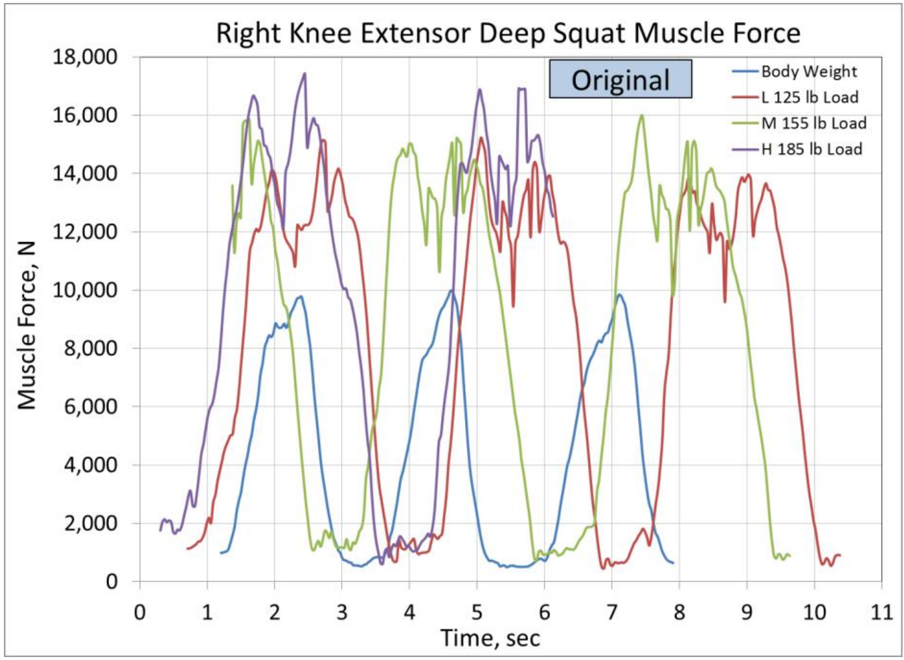
- The adjustments to the knee area resulted in the muscles wrapping around the knee correctly throughout the entire range of motion
- The muscle force at the knee was reduced from the original unmodified model by about 40 percent.
- The images are from an OpenSim simulation of a deep squat that results in a knee angle greater than $90^o$.



Knee Joint After Modifications to the Wrap Surface and Muscle Path Points

# Comparing Results – Original and Modified Models

- The plots below show the deep squat knee extensor muscle force calculated by an OpenSim static optimization run for both the original and modified models.
- Muscle force is the sum of the force for the three Vastus and the Rectus Femoris muscles.
- Plots are from data taken in April, 2014 and are for illustration only.



# Expected Knee Forces

The following table summarizes the knee forces obtained by various authors as collected by Escamilla [2]. The knee forces calculated using the modified OpenSim knee model are within the range of the values outlined below.

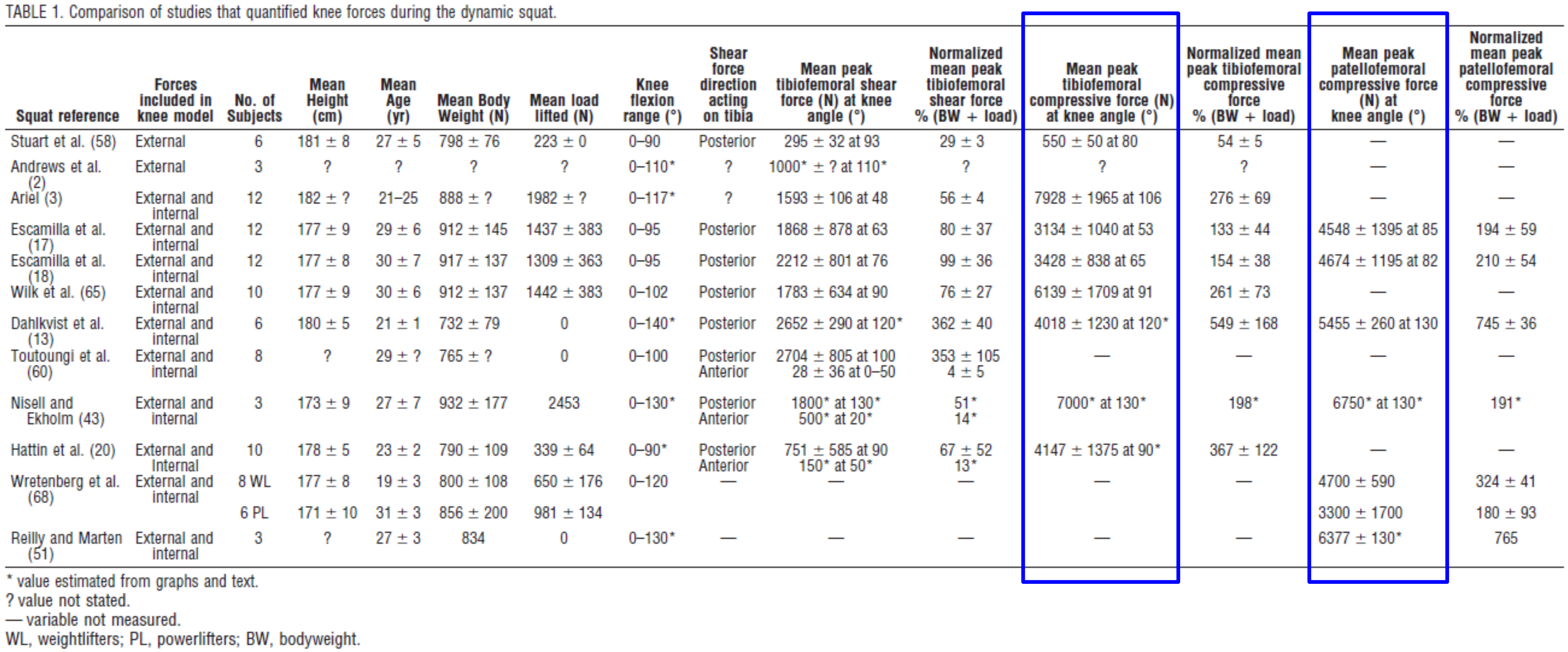


TABLE 1. Comparison of studies that quantified knee forces during the dynamic squat.

| Squat reference | Forces included in knee model | No. of Subjects | Mean Height (cm) | Mean Age (yr) | Mean Body Weight (N) | Mean load lifted (N) | Knee flexion range (°) | Shear force direction acting on tibia | Mean peak tibiofemoral shear force (N) at knee angle (°) | Normalized mean peak tibiofemoral shear force % (BW + load) | Mean peak tibiofemoral compressive force (N) at knee angle (°) | Normalized mean peak tibiofemoral compressive force % (BW + load) | Mean peak patellofemoral compressive force (N) at knee angle (°) | Normalized mean peak patellofemoral compressive force % (BW + load) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stuart et al. (58) | External | 6 | 181 ± 8 | 27 ± 5 | 798 ± 76 | 223 ± 0 | 0–90 | Posterior | 295 ± 32 at 93 | 29 ± 3 | 550 ± 50 at 80 | 54 ± 5 | — | — |
| Andrews et al. (2) | External | 3 | ? | ? | ? | ? | 0–110* | ? | 1000* ± ? at 110* | ? | ? | ? | — | — |
| Ariel (3) | External and internal | 12 | 182 ± ? | 21–25 | 888 ± ? | 1982 ± ? | 0–117* | ? | 1593 ± 106 at 48 | 56 ± 4 | 7928 ± 1965 at 106 | 276 ± 69 | — | — |
| Escamilla et al. (17) | External and internal | 12 | 177 ± 9 | 29 ± 6 | 912 ± 145 | 1437 ± 383 | 0–95 | Posterior | 1868 ± 878 at 63 | 80 ± 37 | 3134 ± 1040 at 53 | 133 ± 44 | 4548 ± 1395 at 85 | 194 ± 59 |
| Escamilla et al. (18) | External and internal | 12 | 177 ± 8 | 30 ± 7 | 917 ± 137 | 1309 ± 363 | 0–95 | Posterior | 2212 ± 801 at 76 | 99 ± 36 | 3428 ± 838 at 65 | 154 ± 38 | 4674 ± 1195 at 82 | 210 ± 54 |
| Wilk et al. (65) | External and internal | 10 | 177 ± 9 | 30 ± 6 | 912 ± 137 | 1442 ± 383 | 0–102 | Posterior | 1783 ± 634 at 90 | 76 ± 27 | 6139 ± 1709 at 91 | 261 ± 73 | — | — |
| Dahlkvist et al. (13) | External and internal | 6 | 180 ± 5 | 21 ± 1 | 732 ± 79 | 0 | 0–140* | Posterior | 2652 ± 290 at 120* | 362 ± 40 | 4018 ± 1230 at 120* | 549 ± 168 | 5455 ± 260 at 130 | 745 ± 36 |
| Toutoungi et al. (60) | External and internal | 8 | ? | 29 ± ? | 765 ± ? | 0 | 0–100 | Posterior<br>Anterior | 2704 ± 805 at 100<br>28 ± 36 at 0–50 | 353 ± 105<br>4 ± 5 | — | — | — | — |
| Nisell and Ekholm (43) | External and internal | 3 | 173 ± 9 | 27 ± 7 | 932 ± 177 | 2453 | 0–130* | Posterior<br>Anterior | 1800* at 130*<br>500* at 20* | 51*<br>14* | 7000* at 130* | 198* | 6750* at 130* | 191* |
| Hattin et al. (20) | External and Internal | 10 | 178 ± 5 | 23 ± 2 | 790 ± 109 | 339 ± 64 | 0–90* | Posterior<br>Anterior | 751 ± 585 at 90<br>150* at 50* | 67 ± 52<br>13* | 4147 ± 1375 at 90* | 367 ± 122 | — | — |
| Wretenberg et al. (68) | External and internal | 8 WL | 177 ± 8 | 19 ± 3 | 800 ± 108 | 650 ± 176 | 0–120 | — | — | — | — | — | 4700 ± 590 | 324 ± 41 |
|  |  | 6 PL | 171 ± 10 | 31 ± 3 | 856 ± 200 | 981 ± 134 |  |  |  |  |  |  | 3300 ± 1700 | 180 ± 93 |
| Reilly and Marten (51) | External and internal | 3 | ? | 27 ± 3 | 834 | 0 | 0–130* | — | — | — | — | — | 6377 ± 130* | 765 |

* value estimated from graphs and text.
? value not stated.
— variable not measured.
WL, weightlifters; PL, powerlifters; BW, bodyweight.

2. Escamilla, R. F., Knee Biomechanics of the Dynamic Squat Exercise, Medicine & Science in Sports & Exercise, Vol. 33, Issue 1, pp 127-141, January 2001.

# Concluding Remarks

- The OpenSim Arnold model includes improved muscle parameters and the addition of wrap surfaces.
- This model works well for walking, running and similar motions.
- The squat exercises that the Digital Astronaut Project is evaluating involve high knee and hip angles.
- Abnormalities were observed in the model at the knee including some muscles with unrealistically high forces, muscle forces suddenly dropping to zero and muscles not following their wrap surfaces.
- The cylindrical wrap surface at the knee was modified and additional path points were added to the four muscles attached to the patella.
- The model was modified during the mid 2014 timeframe and has been used for all subsequent OpenSim analyses.
- The results obtained using the modified model are within the range of the expected forces reported in literature.