Biomechanical comparison of the long jump of athletes with and without a below the knee amputation

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CONCLUSIONS

- Our research provides important information about long jump performance in athletes with and without a below the knee amputation and provides the first 3D joint kinetic data for a full approach/ full effort long jump.
- We found that experienced long jumpers with below the knee amputation have **different net horizontal velocities and impulses** during the take-off step of the long jump compared to experienced non-amputee long jumpers.
- World class long jumpers with a below the knee amputation use a **fundamentally different technique** for long jump.
- **Use of the prosthesis dictates technique** in athletes with a below the knee amputation by allowing the athlete to store and return elastic energy in the carbon fiber prosthesis and to generate positive work from the muscles surrounding the hip joint**. Importantly, all of the energy that is stored in the prosthesis must be generated by the muscular work of the athlete with an amputation during both the run-up and take-off phases.** However use of the prosthesis does not dictate movement patterns; use of a running-specific prosthesis results in greater individual variability in joint movements compared to non-amputees (e.g. knee joint angle).
- Because use of a passive-elastic running-specific prosthesis **limits top speed** [13] and run up speed is an important determinant of jump distance, our results suggest that **use of a prosthesis is a disadvantage for the long jump**.
- We found that experienced long jumpers with a below the knee amputation that take off from their affected leg have better technique than experienced non-amputee long jumpers, suggesting that **use of a prosthesis provides an advantage** for the long jump.
- The long jump is a **complex task** that relies on both speed and technique. At this point in time we cannot weigh the independent effects of speed and technique against each other because they cannot be completely separated and cannot quantify the independent contributions of each factor.
- Our research shows, that long jumpers with running-specific prostheses and non amputee long jumpers use **substantially different movement techniques**. The comparison of performance

limiting factors of those different techniques is not possible at this stage. A factor providing an advantage in one technique might be disadvantageous for the other and vice versa.

- **At this stage of the research, we cannot state that Markus Rehm's prosthesis does or does not provide him with an overall advantage.**
- We plan to continue our research to better understand the combination of mechanical factors that influence long jump performance and the use of running-specific prostheses.

BACKGROUND

What determines long jump performance?

- Long jump performance is determined by the ability to achieve **a fast sprinting speed during the run up** and to utilize **an efficient take-off technique** [1-11].
- Long jump performance has a strong correlation with **run up speed**, such that a faster speed combined with the same technique would result in a longer jump.
- An optimal **take-off technique** for non-amputees includes lowering the center of mass during the second to last step, moving or ''pivoting'' over a nearly straight take-off leg to generate a high vertical velocity while minimizing losses in horizontal velocity, such that better technique combined with the same run up speed would result in a longer jump.
- Changes in **vertical velocity** have a **greater influence on jump distance** than equivalent changes in horizontal velocity during the take-off step [11, 12].
- The success of the pivot is dependent on **approach speed** and **leg muscle strength to control the pivot** [12] in non-amputees.
- For sub-maximal long jumps in non-amputees, the **ankle joint absorbs and returns the largest amount of energy** during the take-off [10]. We do not yet know how the ankle, knee, and hip joints contribute to a full approach long jump in amputees or non-amputees.
- There are no published data on amputee long jumping with a take-off from the affected leg of athletes jumping longer than 6.42 m.

What are running-specific prostheses?

- Running-specific leg prostheses (RSPs) are passive-elastic devices made of carbon fiber that are used to allow running in people with a below the knee amputation.
- RSPs are attached to a rigid socket that encompasses the residual limb and are thus in series with, or beneath, the residual limb.
- RSPs allow for mechanical energy storage and return, similar to tendons and ligaments of biological limbs; but do not simulate the action of muscle fibers because **RSPs cannot generate energy or power by themselves**.
- Socket pistoning (movement of the residual limb inside the socket) may decrease elastic energy storage and return and the transfer of energy to the rest of the leg.
- Unlike biological legs and feet, RSPs have **no sensory feedback, no control, cannot flex for ground clearance and there is no ability to change the stiffness dynamically**.
- Athletes with a unilateral below the knee amputation using RSPs have **asymmetrical biomechanics** during running and sprinting between their affected and unaffected legs, such as 9% less average vertical ground reaction forces in the affected compared to unaffected leg across a wide range of speeds, and 18% less leg stiffness in the affected compared to unaffected leg at 10 m/s [13, 14].
- **Use of RSPs limits top speed** due to impaired ground reaction force generation [13, 14] and worsens stability and balance compared to non-amputees [15, 16].

RESEARCH QUESTION

General research question: **How does use of a running-specific prosthesis affect long jump performance in athletes with a leg amputation compared to non-amputees?**

Specific questions:

Run-up speed:

How do experienced long jumpers with a below the knee amputation and non-amputee long jumpers differ with respect to a) maximum sprinting speed and b) speed during the long jump approach?

Technique:

1) Do experienced long jumpers with a below the knee amputation that use a running specific prosthesis have a different long jump technique than experienced non-amputee long jumpers?
2) Is the long jump technique dictated by the running specific prosthesis?

Good technique during take-off results from: **a)** maximizing horizontal and vertical velocities, **b)** minimizing the net horizontal braking impulse and maximizing the vertical impulse, and **c)** minimizing energy loss and maximizing energy output of the center of mass, ankle or RSP, knee, and hip joints.

RESEARCH METHODS

Participants

- Three of the best male long jumpers (including Markus Rehm) with a below the knee amputation and seven experienced non-amputee long jumpers volunteered to participate in the study (mean ± SD: age 26 ± 2 & 25 ± 3 yrs; mass 78.7 ± 9.8 kg & 80.1 ± 6.2 kg; height 1.83 ± 0.04 m & 1.82 ± 0.07 m).
- Each participant with an amputation used their affected leg as their take-off leg. Three non-amputee participants used their left leg as their take-off leg and four used their right leg as their take-off leg.
- At the time of the study, all long jumpers with a below the knee amputation had best official record jumps of 7.43 ± 0.99 m and non-amputee long jumpers had best official record jumps of 7.65 ± 0.65 m.
- All participants provided written informed consent according to the Institutional Ethics Review Committee.
- Testing took place at German Sports University Cologne indoor track and one athlete with an amputation and one non-amputee were analyzed at the Japan Institute of Sports Sciences.

Long jump and top speed trials

- Athletes completed their typical warm up (~30 minutes)
- Day 1: athletes completed a series of maximum distance long jumps, which simulated competition jumps, while we measured their speeds and biomechanics.
- Day 2: athletes completed a series of maximum speed sprints, while we measured their speeds and biomechanics.
- Measurements: the forces exerted on the ground were measured with one force platform (40x60 cm, Kistler, Winterthur, Switzerland) embedded in the long jump runway at the take-off board and with four force platforms (90x60 cm, Kistler, Winterthur, Switzerland) along the track. Prior to jumping or sprinting, we placed reflective markers at anatomical reference points on subject's legs, torso, and arms using two-sided tape and measured their movements with a 3D motion capture system (Vicon, Oxford, UK). We measured speed with a laser gun (LAVEG, Jenoptik, Jena, Germany).
- To quantify the long jump techniques used by long jumpers with a leg amputation and non-amputee long jumpers, we calculated 3D joint motions, moments, powers, and work using a detailed digital movement analysis model of the human body (Alaska, Chemnitz, Germany). The theoretical jump distance of each athlete was determined from the take-off velocity and take-off angle of the center of mass, assuming a parabolic flight curve [17].

RESULTS

- We compared the best jumps achieved by each athlete. Long jumpers with a below the knee amputation jumped <u>7.25 ± 0.77 m</u> and non-amputee long jumpers jumped <u>7.27 ± 0.45 m</u>. Markus Rehm (MR) achieved a distance of 7.96 m, which was 0.5% and 22.2% higher compared to the highest and lowest values of non-amputees.

Speed: Experienced long jumpers with a below the knee amputation had **slower average top speeds and slower average run-up speeds** compared to non-amputee long jumpers.

- The top speed during sprint trials without take-off for long jumpers with a below the knee amputation was 9.38 ± 0.55 m/s and for non-amputee long jumpers was 10.15 ± 0.42 m/s. **MR's' top speed** was 9.98 m/s, which was between the fastest and slowest values of non-amputees.
- The average horizontal run-up speed at touch-down of the take-off step for long jumpers with a below the knee amputation was 8.71 ± 0.56 m/s and for non-amputee long jumpers was 9.39 ± 0.36 m/s**.** **MR's horizontal run-up speed at touch-down** was 9.32 m/s, which was between the highest and lowest values of non-amputees.

Technique: Experienced long jumpers with a below the knee amputation had a **more efficient technique** compared to non-amputee long jumpers.

Velocity (or speed) during the take-off step

- **The loss in horizontal velocity was less for jumpers with a below the knee amputation compared to non-amputees.** The loss in horizontal velocity during the take-off step for long jumpers with a below the knee amputation was 0.60 ± 0.03 m/s and for non-amputee jumpers was 1.09 ± 0.23 m/s, a difference of 45.0%. **MR's loss in horizontal velocity** was 0.64 m/s, which was 57.2% and 24.5% lower compared to the fastest and slowest values of non-amputees.
- **The net vertical velocity for jumpers with a below the knee amputation was not different than that of non-amputees.** Net vertical velocity during the take-off step for long jumpers with a below the knee amputation was 3.39 ± 0.42 m/s and for non-amputee jumpers was 3.37 ± 0.32 m/s. **MR's net vertical velocity** was 3.68 m/s, which was between the highest and lowest values of non-amputees.
- **The resultant take-off velocity for jumpers with a leg amputation was not different than that of non-amputees.** Resultant take-off velocity for long jumpers with a below the knee amputation was 8.60 ± 0.60 m/s at 18.4 ± 1.6° above horizontal and for non-amputee jumpers was 8.73 ± 0.32 m/s at 18.0 ± 2.0° above horizontal. **MR's resultant take-off velocity** was 9.24 m/s at 18.3°, which was 1.4% and 11.9% greater compared to the highest and lowest velocities of non-amputees.

Impulse (or the integral of force with respect to time) during the take-off step

- **The contact times during the take-off step for jumpers with a below the knee amputation were not different than those of non-amputees.** Contact time during the take-off step for long jumpers with a below the knee amputation was 0.131 ± 0.015 s and for non-amputee jumpers was 0.125 ± 0.010 s. **MR's contact time** was 0.118 s, which was between the highest and lowest values of non-amputees.
- **The net horizontal impulse for jumpers with a leg amputation was different than that of non-amputees.** The magnitude of the net horizontal impulse during the take-off step for long jumpers with a below the leg amputation was 0.064 ± 0.009 BW*s and for non-amputee jumpers was 0.111 ± 0.031 BW*s. **The magnitude of MR's net horizontal impulse** was 0.071 BW*s, which was 57.3% and 14.8% lower compared to the highest and lowest values of non-amputees.
- **The vertical impulse for jumpers with a below the knee amputation was not different than that of non-amputees.** Vertical impulse during the take-off step for long jumpers with a below the knee amputation was 0.466 ± 0.031 BW*s and for non-amputee jumpers was 0.416 ± 0.077 BW*s. **MR's vertical impulse** was 0.480 BW*s, which was between the highest and lowest values of non-amputees.

- **The ratio of vertical to net horizontal impulse for jumpers with a below the knee amputation was greater than that of non-amputees.** The ratio of vertical to net horizontal impulse during the take-off step for long jumpers with a below the knee amputation was 7.37 ± 0.65 and for non-amputee jumpers was 3.82 ± 0.54. **MR's ratio of vertical to net horizontal impulse** was 6.74, which was 49.5% and 115.3% higher compared to the highest and lowest values of non-amputees.

Mechanical energy during take-off

- **The ratio of positive to negative center of mass work was higher for jumpers with a below the knee amputation compared to non-amputees.** The average ratio of positive to negative center of mass work for long jumpers with a below the knee amputation was 113.5 ± 13.1% and for non-amputee long jumpers was 56.7 ± 15.9%. **MR's average ratio of positive to negative center of mass work** was 100.1%, which was 30.5% and 183.0% higher compared to the highest and lowest values of non-amputees. Indeed, all amputee jumpers performed net positive center of mass work.
- **The RSP and joint energy patterns were different for jumpers with a leg amputation compared to non-amputees.** In jumpers with a leg amputation, 81% (MR: 84%) of the energy was absorbed by the prosthesis and 15% (MR:14%) was absorbed by the knee; whereas in non-amputee jumpers energy was absorbed almost equally by the hip, knee and below knee joints (ankle + toes metatarsal - phalangeal joint). In jumpers with a leg amputation, 73% (MR: 76%) of the positive joint work was performed by energy return from the prosthesis, 22% (MR: 20%) by positive work of the hip and 6% (MR: 4%) by positive work of the knee. In non-amputee athletes, energy generation was more equally distributed across the hip: 40%, knee: 25%, and ankle: 34%.
- **The RSP energy return for jumpers with a leg amputation was higher than the below knee joint energy return for non-amputees.** The energy return during the take-off step for long jumpers with a below the knee amputation was 3.57 ± 0.97 J/kg and for non-amputee jumpers was 1.96 ± 0.28 J/kg. **MR's RSP energy return** was 4.41 J/kg, which was 88.2% and 192.8% higher compared to the highest and lowest values of non-amputees.
- **The knee joint energy return/generation for jumpers with a below the knee amputation was less than that for non-amputees.** The energy return/generation during the take-off step for long jumpers with a below the knee amputation was 0.29 ± 0.03 J/kg and for non-amputee jumpers was 1.45 ± 0.50 J/kg. **MR's knee joint energy return/generation** was 0.26 J/kg, which was 87.6% and 56.1% lower compared to the highest and lowest values of non-amputees.
- **The hip joint energy return/generation for jumpers with a below the knee amputation was less than that for non-amputees.** The energy return during the take-off step for long jumpers with a below the knee amputation was 1.06 ± 0.24 J/kg and for non-amputee jumpers was 2.28 ± 0.76 J/kg. **MR's hip joint energy return/generation** was 1.17 J/kg, which was 69.1% and 22.9% lower compared to the highest and lowest values of non-amputees.

General findings

- **The peak knee flexion angle for jumpers with a below the knee amputation was less than that for non-amputees.** The peak knee flexion angle during the take-off step for jumpers with a below the knee amputation was 27.9 ± 3.2° and for non-amputee jumpers was 48.2 ± 5.3°. **MR's peak knee flexion angle** was 24.5°. Analysis of different jumps of the same subjects also indicated that the variability in the knee joint angle at toe-off (knee angle at the end of the take-off stance phase) is higher in athletes with a leg amputation. However, the number of trials was small and therefore further analysis of this variability is needed.

- **The shape of the vertical ground reaction force (GRF) curve during the stance phase of sprinting for jumpers with leg amputation was different than that of non-amputees.** While the curve of the vertical GRF of non-amputees showed a high impact peak in the first part of the stance phase, the vertical force traces of the amputees showed a curve shape close to a half-sinus. This underlines the elastic behaviour of the prostheses.

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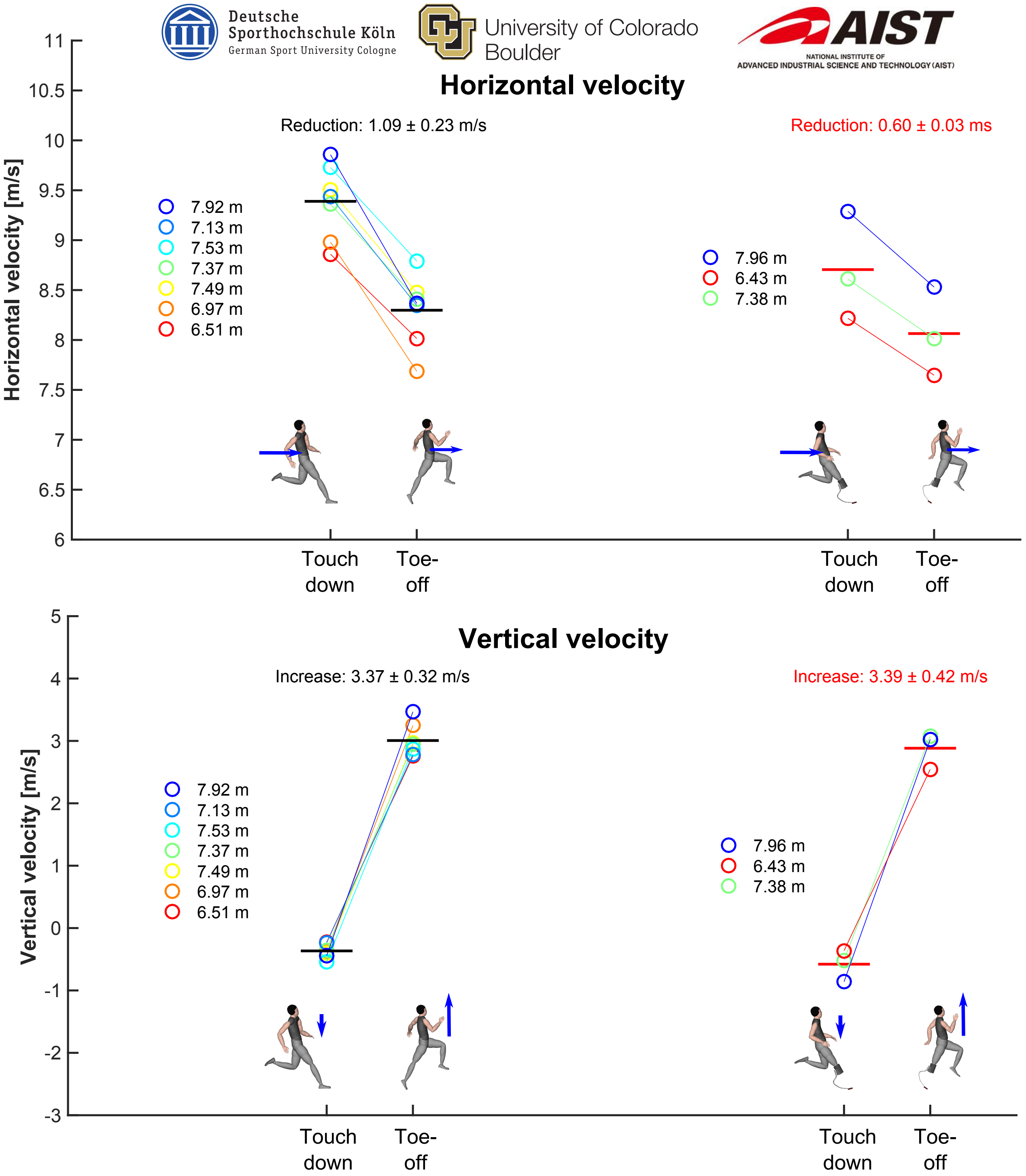
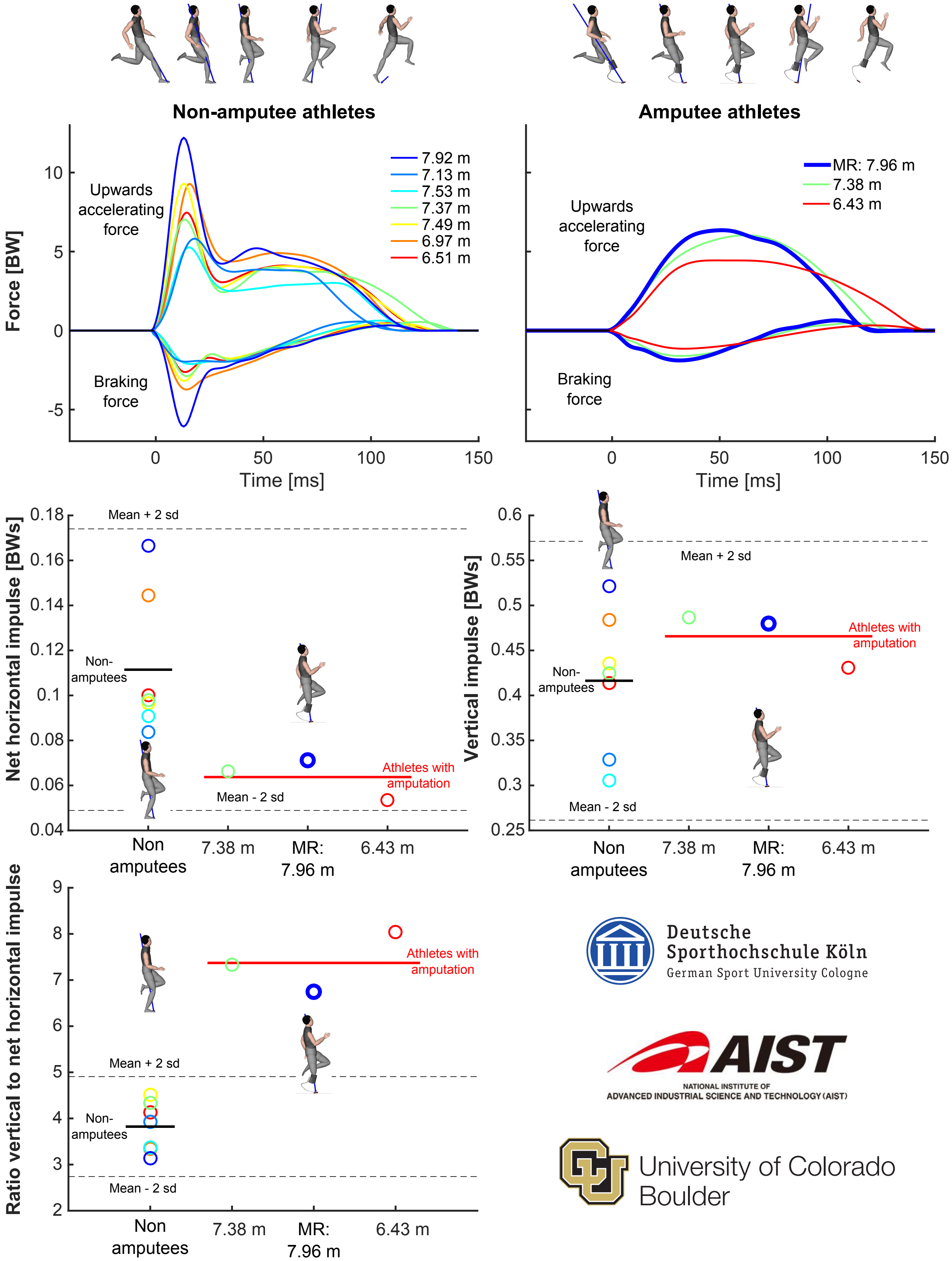


Horizontal (top figure) and vertical (bottom figure) velocities and changes of velocitiy during the foot-ground contact of the take-off phase of the non-amputee jumpers (left) and long jumpers with a below the knee amputation (right). Each circle represents the velocity at touchdown and at toe-off of the best jump of one athlete. The blue circle represents the best jump of Markus Rehm. Mean values of the related groups are indicated by the horizontal bars.

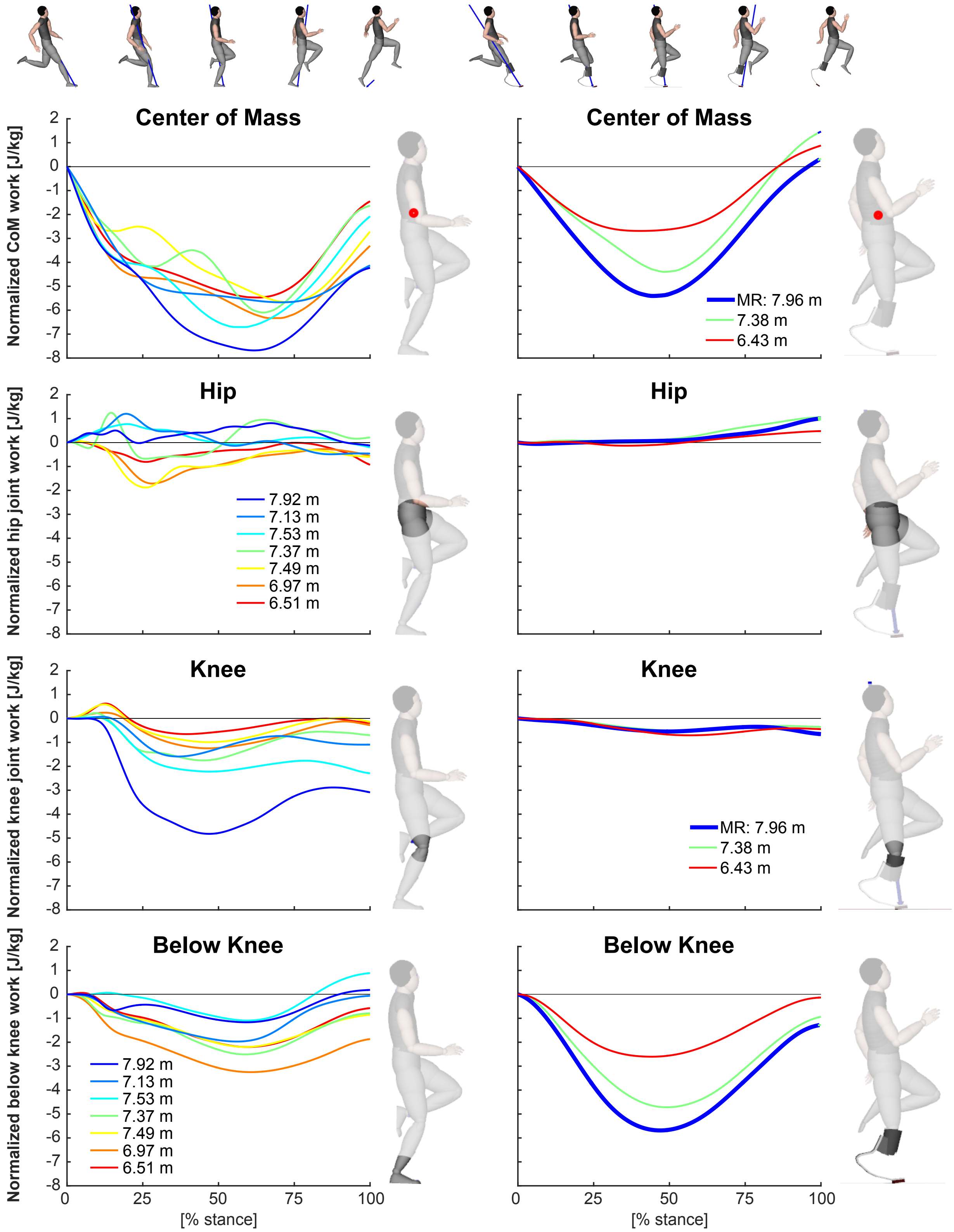


First row: Vertical and horizontal ground reaction force curves in units of body weight during foot-ground-contact during the take-off phase. Each line represents the best jump of one athlete. The bold blue line (right) represents Markus Rehm's (MR) jump. Mean values of the related groups are indicated by the horizontal bars.

Second row: Net horizontal impulse (left) and vertical impulse (right) in units of bodyweight times second. The impulse is a measure of the braking or propulsive effect of force acting over a period of time. Each circle represents the impulses of the best trial of one athlete. The blue bold circle represents the best trial of Markus Rehm (MR).

Third row: Ratio of vertical to horizontal impulse. Each circle represents the impulses of the best trial of one athlete. The blue bold circle represents the best trial of Markus Rehm (MR).

The data show that the movement technique of long jumpers with a below the knee amputation is more efficient. Long jumpers with a below the knee amputation generate the same vertical impulse at take-off, i.e. they experience the same average acceleration upwards at take-off, but have less slowing of their forward velocities compared to non-amputees(second row and third row).



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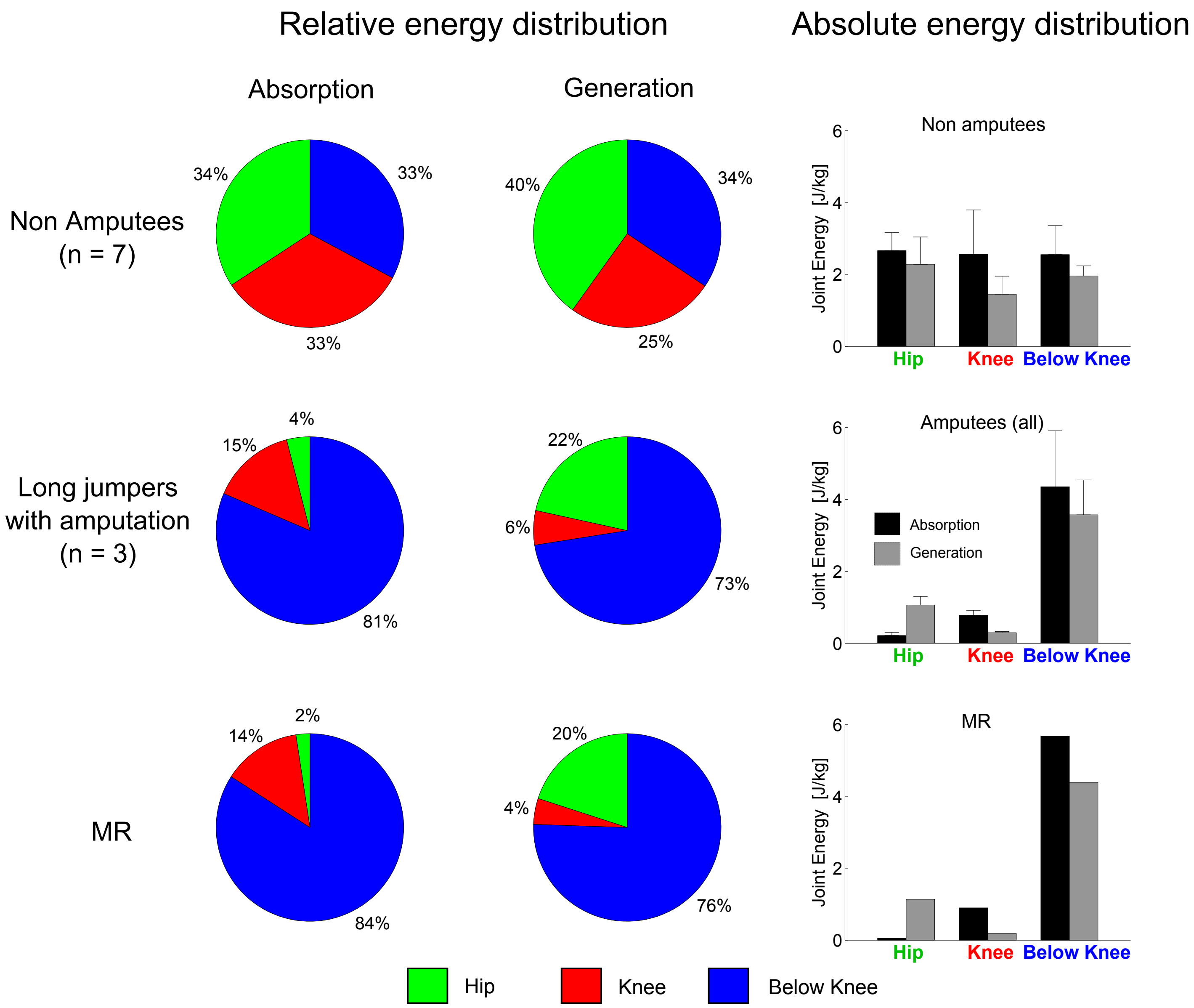
Mechanical work of the center of mass (CoM, top row), hip joint (second row), knee joint (third row) and ankle joint or prosthesis, respectively (bottom row) of the non-amputees (left column) and long jumpers with amputation (right column). Each line represents the best jump of each athlete. The bold blue line (right) represents Markus Rehm's (MR) jump. Negative mechanical work is a measure for how much energy a system is absorbing (descending curves), and positive mechanical work is a measure for how much energy the system is generating (ascending curves).
The data show that the prosthesis dictates the movement technique in athletes with amputation and that this movement technique is fundamentally different compared to non-amputees. With the touch-down, the energy of the athletes decreases (top row, center of mass) and then increases in the second part of the take-off phase. In jumpers with an amputation CoM work is in phase with the energy absorption of the prosthesis (bottom row right). Long jumpers with amputation store a lot of energy during touch-down in the passive elastic prosthesis, which returns a high portion of that energy later during push-off. At the same time, the hip joint performs positive work. This leads to a very efficient jumping technique in athletes with an amputation compared to non-amputee jumpers (114% vs. 57%).



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The pie charts show each joint's contribution to the total mechanical energy. During the take-off step, energy is absorbed / stored and generated / returned by each joint. While in non-amputees all joints contribute remarkably similar to the total mechanical work (first row), in ahletes with a below the knee amputation the prosthesis plays the major role (81% absorption and 73% generation). Importantly, all of the energy that is stored in the prosthesis must be generated by the muscular work of the athlete with an amputation during both the run-up and take-off phases.