2017 International Conference on Rehabilitation Robotics (ICORR)
QEII Centre, London, UK, July 17-20, 2017.

Evaluation of 3D Printed Anatomically Scalable Transfemoral Prosthetic Knee

Tyagi Ramakrishnan[1], Millicent Schlafly[2] and Kyle B Reed[3]

Abstract— **This case study compares a transfemoral amputee's gait while using the existing Ossur Total Knee 2000 and our novel 3D printed anatomically scalable transfemoral prosthetic knee. The anatomically scalable transfemoral prosthetic knee is 3D printed out of a carbon-fiber and nylon composite that has a gear-mesh coupling with a hard-stop weight-actuated locking mechanism aided by a cross-linked four-bar spring mechanism. This design can be scaled using anatomical dimensions of a human femur and tibia to have a unique fit for each user. The transfemoral amputee who was tested is high functioning and walked on the Computer Assisted Rehabilitation Environment (CAREN) at a self-selected pace. The motion capture and force data that was collected showed that there were distinct differences in the gait dynamics. The data was used to perform the Combined Gait Asymmetry Metric (CGAM), where the scores revealed that the overall asymmetry of the gait on the Ossur Total Knee was more asymmetric than the anatomically scalable transfemoral prosthetic knee. The anatomically scalable transfemoral prosthetic knee had higher peak knee flexion that caused a large step time asymmetry. This made walking on the anatomically scalable transfemoral prosthetic knee more strenuous due to the compensatory movements in adapting to the different dynamics. This can be overcome by tuning the cross-linked spring mechanism to emulate the dynamics of the subject better. The subject stated that the knee would be good for daily use and has the potential to be adapted as a running knee.**

I. INTRODUCTION

The human knee is a versatile and complex joint. It is a condylar joint formed at the interface of the distal femur and the proximal tibia bones. The knee is controlled by several femoral and tibial muscles that help in the joint's nuanced control and weight bearing. From the sagittal plane, the knee joint flexion involves rotation and anterior translation of the femoral condyle over the proximal tibial surface. The knee also utilizes the Anterior and Posterior Cruciate ligaments that form integral physical parts in the performance of the human knee. Alterations such as reconstruction of the ligaments, that may be due to injuries, result in a dramatic change in the person's gait [1]. This is amplified if a person undergoes transfemoral amputation and loses the knee and ankle joint. Designing better prosthetics is then vital to restore an amputee's gait quality and function.

[1]Tyagi Ramakrishnan is a Doctoral Candidate in Mechanical Engineering at the University of South Florida, 4202 E Fowler Ave, Tampa, FL, 33620 tyagi@mail.usf.edu

[2]Millicent Schlafly is a student in Mechanical Engineering at the University of South Florida, 4202 E Fowler Ave, Tampa, FL, 33620 mschlafly@mail.usf.edu

[3]Kyle B. Reed is faculty with the Department of Mechanical Engineering at the University of South Florida, 4202 E Fowler Ave, Tampa, FL, 33620 kylereed@usf.edu

Design of prosthetic knees fall into one of two categories: Endo and Exo. Endo-prosthetic knees are biomimetic and follow the contours of the femoral condyles and the tibial surface [2]. They are usually surgically implanted onto patients during Total Knee replacement. Exo-prosthetic knees are fitted on amputees and lie outside the body cavity. These exo-prosthetic knees can be further classified into passive and active mechanisms [3][4]. While active knees show tremendous potential in the knee's ability to adapt to different walking speeds and better replicate the normal gait, designs are just beginning to enter the market [5]. Active knees remain expensive, difficult to prescribe, and require extensive training. Currently, they are more intended for transfermoral amputees who require more control from their prosthesis.

There are various options of passive knee prosthetics available for amputees with control level classifications from K0 to K4. Single-axis knees allow for limited movement but provide greater assistance and are sometimes ideal for transfemoral amputees who have lower levels of control (K0 – K2). Another popular choice is the polyaxial knee with multiple centers of rotation and is often based on a four bar mechanism [6][7][8]. The mechanical components of these designs find their foundation in the physical components of an actual knee: the tibia, femur, PCL, and ACL. Movement about a more posterior axis allows for greater control and gives rise to greater stability in mechanisms that lock in a load bearing stance.

The Ossur Total Knee is an example of a common polyaxial mechanism and is used as a comparison in this study. It makes use of hydraulics to adapt to different walking speeds [9]. At longer strides, the hydraulic system provides more resistance to excess flexion and uses that built up energy to assist in the forward swing on the prosthetic leg [10]. The hydraulic design has become typical in better prosthetics that allow for a greater variety of movement and provide a more human-like gait. However, hydraulic knees remain heavy, costly, difficult to personalize and require maintenance. These aspects of prosthetic design are addressed in the anatomically scalable transfemoral knee.

3D printing in prosthetics is a recent development that has been successfully implemented in making cheap prosthetic hands for children [11]. This is a logical step for incremental development because a child's arm does not have to take up excessive loads such as a prosthetic knee that will be constantly taking up loads that are equivalent to the user's body weight or more depending on the tasks. This enables 3D printed arms to be made of cheap materials such as Acrylonitrile Butadiene Styrene (ABS) and polylactide

978-1-5386-2295-7/17/$31.00 ©2017 IEEE

(PLA). Lower limb prosthetics were developed starting with custom made sockets [12] and implants for knee replacement [13]. The Socket designs are improved because the 3D point cloud from scans can be used to develop a custom profile for the prosthetic socket. This improves fit and comfort for the amputee, researchers have also demonstrated that the sockets can have embedded sensors that can monitor the residual limb's condition [14]. Similarly, for knee replacement, endo prosthetic development using 3D printing can be used to make molds for casting titanium components that can then be implanted into the patient.

The anatomically scalable transfemoral prosthetic knee presented here is 3D printed using carbon-fiber and nylon composite. It is designed to have a polyaxial cross-linked spring mechanism and utilizes gear mesh locking to lock the knee during stance phase. The modeling of the ACL and the PCL in the cross-linked spring mechanism provides similar swing assistance as hydraulic mechanisms in the Ossur Total Knee. Due to 3D printing and modeling technology, the dimensions of the anatomically scalable transfemoral prosthetic knee can be personalized and scaled to match that of the patient quickly and cheaply. Alterations can be easily made to accommodate patients with a wider range of control than the Ossur Total Knee. Finally, the carbon-fiber nylon composite composition of the anatomically scalable transfemoral prosthetic knee compared to metal is lighter and would require less metabolic cost from the user.

II. DESIGN

The 3D printed anatomically scalable transfemoral prosthetic knee used in this study has two parts made out of carbon-fiber nylon composite. This knee has a gear mesh locking mechanism that is aided by a cross-linked spring mechanism that acts like the ACL and PCL of the human body, shown in Figure 1. The springs used for this study were metallic; in future designs, we can explore the use of rubber and composite springs to reduce the mass of the knee system. A preliminary version of this knee was used to obtain the mechanism's kinematics [15]. The femoral gear attaches to the socket and the tibial gear holds the foot and pylon assembly, as shown in Figure 2(a). The femoral and tibial gear are designed based on condylar radius of an adult human, which ranges from 18 – 30mm [16][17][18][19]. The full gears are designed to have 25 teeth at a $14.5°$ pressure angle. The gears are held together by an exterior link that is lasercut out of Delrin, a strong acrylic plastic material. The femoral gear attaches to the socket by means of a conventional titanium pyramid head, a standard prosthetic connecting mechanism. The pylon and foot assembly is connected to the tibia gear by means of a precision fit with a bolt connector. A comparison of the specifications of the two knees is shown in Table I and in Figure 2.

The working of the Ossur Total Knee and the anatomically scalable transfemoral prosthetic knee mechanisms are quite different. The Ossur Total Knee has a five-bar mechanism that is aided by an hydraulic return mechanism. The anatomically scalable transfemoral prosthetic knee uses the

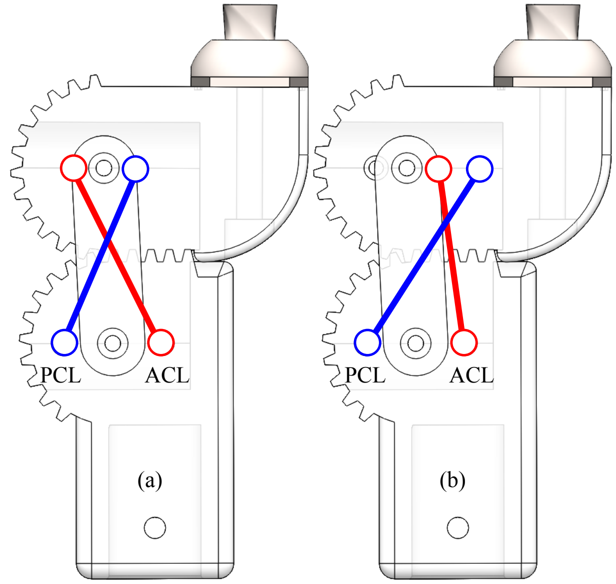

Fig. 1. Spring Configuration. (a) The configuration used in the experiments. (b) Configuration for faster extension.

(a) (b)

Fig. 2. Amputee wearing the 3D printed knee. (a) Side view and (b) Ossur 2000 next to the 3D printed knee.

TABLE I

PROSTHETIC KNEE SPECIFICATIONS

Parameters	Total Knee 2000	Biomimetic Knee
Amputation Level	Transfemoral	Transfemoral
Impact Level	K2 - K4	K2 - K4
Max. Patient Weight	100Kg	110kg
Knee Weight	690g	701.5g
Build height	173mm	185mm
Flexion	160°	180°

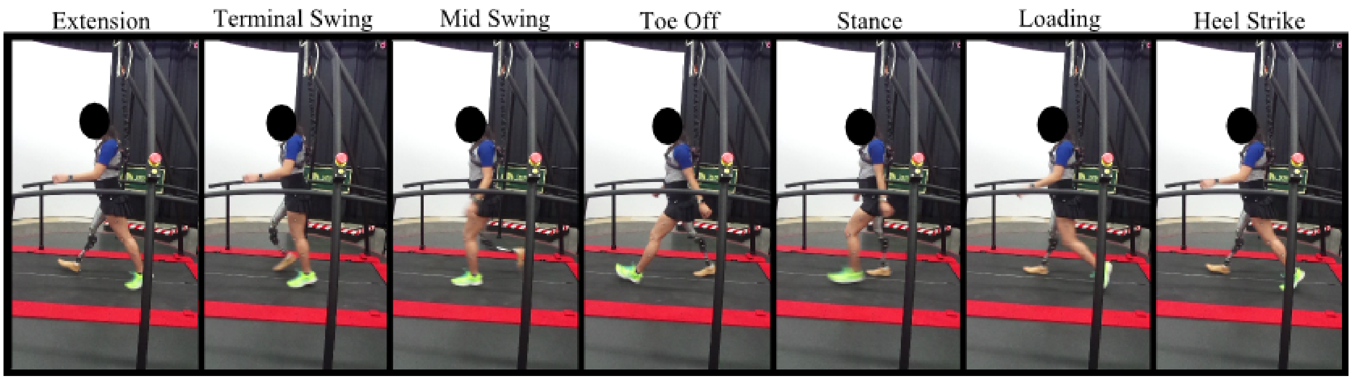

Fig. 3. Walking With the Biomimetic 3D printed Prosthetic Knee on the CAREN system

curvature of the femoral and tibial gears to lock and unlock, while the cross-linked spring mechanism acts as a return mechanisms, shown in Figure 1(a). At heel strike the femur and tibia gear have a hard-stop at full extension after which the loading of the user's weight keeps it locked through stance phase. The gears also play a role in locking as they do not allow the femur and tibia to slide during stance loading. This brings about the gear mesh coupling with a hard-stop and weight-actuated locking mechanism of the 3D printed knee as opposed to the geometric and hard stop locking mechanism of the Ossur Total Knee. The Ossur Total Knee is lighter than the anatomically scalable transfemoral prosthetic knee, as shown in Table I, but this prototype of the anatomically scalable transfemoral prosthetic knee is not optimized to the subject's proportions, it was designed for an adult male. Optimization of the design can bring down the weight and dimensions of the knee making it more compact. The ability to customize prosthetics is of growing interest in the prosthetic community as more prosthetic users prefer components that are made according to their individual preferences. For example, the amputee subject from the study here reported that the ability of the anatomically scalable transfemoral prosthetic knee to flex more than the Ossur allows her to kneel more comfortably.

III. METHODS

The experimental protocol was based on the USF IRB and the subject signed an informed consent form prior to participating. The subject for this experiment is a 37 year old female high functioning transfemoral amputee. The experiments were conducted on the Computer Assisted Rehabilitation Environment (CAREN), which is a state of the art testing environment. The CAREN is equipped to provide continuous motion capture and force plate data collection. The subject walked on the treadmill, shown in Figure 3, at a velocity that is obtained from a standard 10 meter walk test, in this case it was 1.4m/s. Eighteen reflective markers were used for motion capture where the markers were placed to facilitate capturing primary joint, hip, knee, and ankle, motions. The motion capture and kinetic data obtained is processed using a Matlab script that assessed 11 different spatio-temporal, kinematic, and kinetic gait parameters. We also used the Combined Gait Asymmetry Metric [20] to measure the overall asymmetry of the two gait patterns.

IV. RESULTS

The apparent difference between the prosthetic knees can be evaluated using the knee angles, shown in Figure 4. It can be seen that the step time on both the right and left sides take longer on the the biomimetic compared to the Ossur Total Knee. This may be because the amputee uses the Ossur Total Knee everyday and is aware of the knee's nuances that helps her achieve shorter step times. The amputee also reported that she felt the 3D printed knee was lighter and she had to wait for the terminal impact of the knee before she could shift her weight over to the prosthetic. This can be optimized by changing the cross-linked spring linkage inside the knee to help return the shank faster, thereby improving cadence by decreasing step times. Another feature that is clearly seen from the knee angles is the magnitude of maximum flexion. The biomimetic knee has higher peak flexion compared to the Ossur Total Knee due to the lower resistance offered by the internal mechanism. This is another cause for longer flexion times that can be mitigated by changing the configurations of the return mechanism, as shown in Figure 1(b).

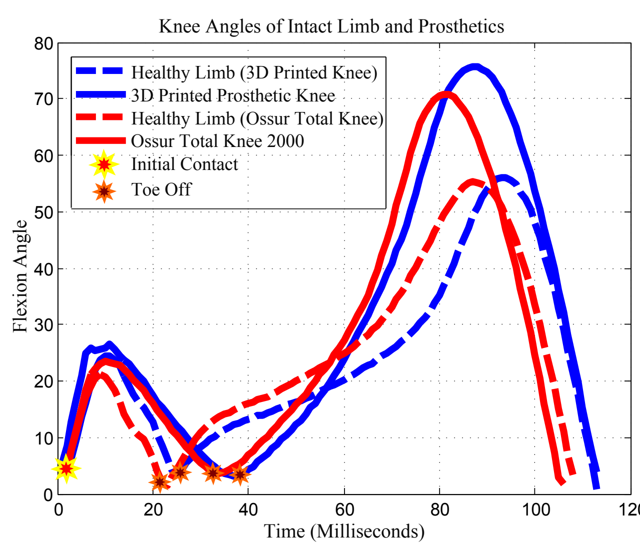

Fig. 4. Comparison of Knee Angles

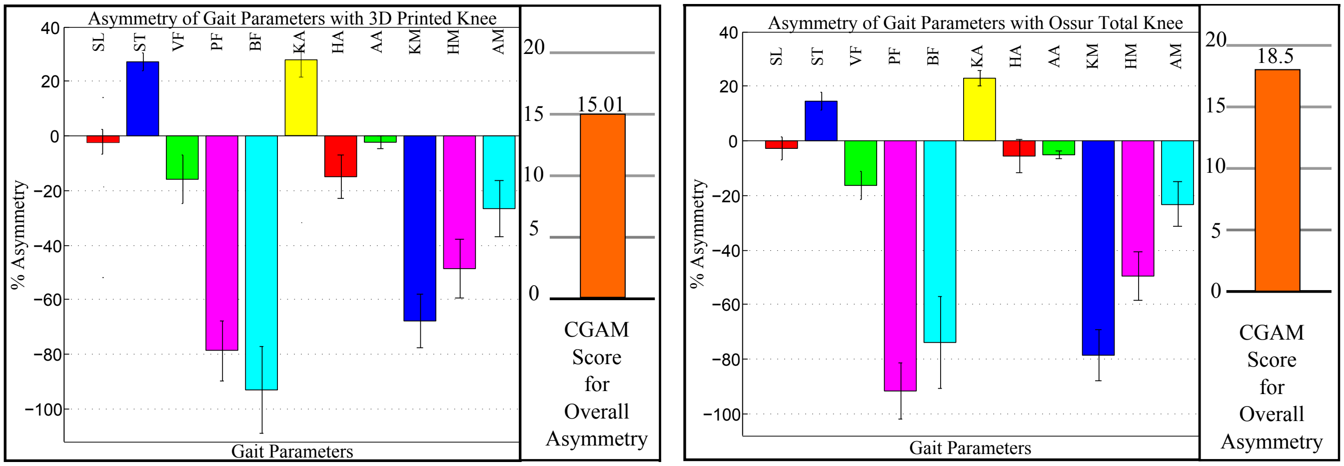

Fig. 5. CGAM Scores; [Legend: SL – Step Length, ST – Step Time, VF – Vertical Force, PF – Push Off Force, BF – Braking Force, KA – Knee Angle, HA – Hip Angle, AA – Ankle Angle, KM – Knee Moment, HM – Hip Moment, AM – Ankle Moment]

To obtain a sense of the overall asymmetry of these two different gait patterns, the Combined Gait Asymmetry Metric (CGAM) scores were calculated [20]. CGAM scores are calculated using a modified Mahalanobis distance [21] that finds the distances using all eleven gait asymmetry parameters. The distances are weighed according to the inverse covariance among the eleven gait parameters shown in Figure 5. This form of combining the asymmetries of different gait parameters gives rise to the CGAM scores that represent the overall asymmetry. The asymmetry observed in knee angles can also be seen in Figure 5, where the average peak knee angle asymmetry of the 3D printed knee is larger than the Ossur Total Knee. This resulted in a larger step time and braking force asymmetry. The magnitude of the CGAM score indicates the degree of overall asymmetry in the person's gait. In this case the subject's gait with the Ossur Total Knee is more asymmetric than the biomimetic knee. However, more symmetric does not necessarily mean it is better for the subject. The subject was more strained while using the biomimetic knee because the system was not optimized to their specific needs. The asymmetry that the subject showed on the Ossur Total Knee seems to be the subject's gait with least strain.

V. DISCUSSION

The 3D printed anatomically scalable transfemoral prosthetic knee is a simple mechanism that has the potential to be customized on a subjective basis using 3D printing. 3D printing prosthetic knees will help bring down the cost of manufacturing while allowing users to choose desired features from the mechanism. This would also allow us to scale the same design over different anatomical sizes from children to adults and also modify them for male and female. This flexibility is not seen with traditional designs that are can only be made at certain sizes and shapes due to the limitations of conventional manufacturing processes.

The results of the experiment show specific differences between the change in gait dynamics between the knees. The gait with the Ossur Total Knee has lower peak joint flexion, symmetric step time, and braking forces. However, gait with the Ossur Total Knee resulted in a overall more asymmetric gait in the CGAM score compared to the gait with the 3D printed knee. This asymmetry may be a result of the subject being more willing to shift her weight onto the Ossur knee because the subject uses it everyday. It is also possible that the subject's compensation to the 3D printed knee's dynamics, such as the higher peak knee flexion, resulted in a more symmetric gait. The 3D printed knee can be improved by adjusting the cross-linked spring mechanism inside the knee to a configuration shown in Figure 1(b) from Figure 1(a). Using an ACL spring with greater stiffness will restrict the peak knee flexion and reduce the total time of knee flexion. Improving overall symmetry of prosthetic gait can bring about more comfortable and stable gait that does not cause long term damage to the residual limb and the musculoskeletal system due to the compensation. The customizable prosthetic knee presented in this paper uses simple design to help the amputee to walk with a lower CGAM score which can benefit them in the long run.

The subject was comfortable with the 3D printed knee from the first fitting. She pointed out that the low resistance provided by the mechanism was better for ambulatory walking and that the knee can potentially be used for running in future iterations. During the experimentation the subject felt that the biomimetic knee forced her to recruit more muscles in her residual limb during gait because she was waiting for the terminal impact of the knee to start the prosthetic leg load bearing.

The subject also felt that the 3D printed knee was lighter and hence the shank took longer in flexion. However, the 3D printed knee is actually slightly heavier than the Ossur Total Knee. This perception of heaviness may be due to a haptic illusion that a subject perceives an object is heavier than it actually is [22][23]. The texture and perceived density of the 3D printed knee may have portrayed the illusion that the 3D printed knee was lighter than the Ossur Total Knee which is made out of metal while the anatomically scalable transfemoral prosthetic knee was made out carbon-fiber and nylon mesh. This perception could also be related to the different moment of inertia caused by the different mass distributions. This is not conclusive and possibly highly subjective. More testing is required in order to check for the effect of perception as well as further developing the 3D printed anatomically scalable transfemoral prosthetic knee design.

3D printing prosthetics allows designs to become more customized and geared for individual specifications as opposed to mass production models that are not customizable. Current materials that can be 3D printed cannot be made with the same strength of molded plastics. This leads to larger and bulkier designs that often end up being heavier than warranted. 3D printing via Fused Deposition Modeling (FDM) which is the most common form of 3D printing runs into the problem of being extremely directional and leads to de-lamination along certain directions. This directionality may work well with carbon fiber and other types of composites but at this point the cost of printing these high strength materials is high. As the industry keeps innovating and improving the viable materials, we are expecting the prices to reduce.

VI. CONCLUSIONS

Comparing the novel 3D printed anatomically scalable transfemoral prosthetic knee to a tried and tested Ossur Total Knee has shown that there is potential for specialized 3D printed knee designs. The simple design of the scalable transfemoral prosthetic knee allowed for the amputee to quickly adjust to its dynamics. The amputee also gave positive feedback regarding the level of use of the anatomically scalable transfemoral prosthetic knee design. Future studies will look at more optimized version that are less straining for the user yet still showcase the overall symmetric gait of the anatomically scalable transfemoral prosthetic knee. This can be accomplished by using a new combination of materials to make the designs lighter and stronger. The existing design could also be modified through changing the configuration of the cross-linked springs to better emulate swing times of the subject.

ACKNOWLEDGMENT

We would like to acknowledge the support of NSF grant No. MRI-1229561. We also would like to thank Visualflo for 3D printing the carbon-fiber and nylon mesh parts of the biomimetic knee.

REFERENCES

[1] R. Ferber, L. R. Osternig, M. H. Woollacott, N. J. Wasielewski, and J.-H. Lee, "Gait mechanics in chronic acl deficiency and subsequent repair," *Clinical biomechanics*, vol. 17, no. 4, pp. 274–285, 2002.

[2] T. Andriacchi, J. Galante, and R. Fermier, "The influence of total knee-replacement design on walking and stair-climbing," *Journal of Bone and Joint Surgery-Series A*, vol. 64, no. 9, pp. 1328–1335, 1982.

[3] M. Cantos, "Pirates & peg legs: A historical look at amputation and prosthetics," *History of Medicine Days*, vol. 14, pp. 16–20, Mar 2005.

[4] D. S. Childress, "Historical aspects of powered limb prostheses," *Clinical prosthetics and orthotics*, pp. 2–13, 1985.

[5] J. L. Johansson, D. M. Sherrill, P. O. Riley, P. Bonato, and H. Herr, "A clinical comparison of variable-damping and mechanically passive prosthetic knee devices," *American journal of physical medicine & rehabilitation*, vol. 84, no. 8, pp. 563–575, 2005.

[6] C. Radcliffe, "Four-bar linkage prosthetic knee mechanisms: kinematics, alignment and prescription criteria," *Prosthetics and orthotics international*, vol. 18, no. 3, pp. 159–173, 1994.

[7] P. Mukul, J. Sadler, and E. Thorsell, "Stanford–jaipur knee joint for trans femoral amputees," in *Proceedings of the 13th world congress of the International Society for Prosthetics and Orthotics, Leipzig, Germany*, 2010, pp. 10–15.

[8] D. Jin, R. Zhang *et al.*, "Kinematic and dynamic performance of prosthetic knee joint using six-bar mechanism," *Journal of rehabilitation research and development*, vol. 40, no. 1, pp. 39–48, 2003.

[9] B. Omarsson, S. G. Karlsson, S. Olafsson, G. Olafsson, and D. Landry, "Prosthetic knee," Jul. 1 2014, uS Patent 8,764,849.

[10] M. B. Silver-Thorn and C. L. Glaister, "Functional stability of transfemoral amputee gait using the 3r80 and total knee 2000 prosthetic knee units," *JPO: Journal of Prosthetics and Orthotics*, vol. 21, no. 1, pp. 18–31, 2009.

[11] J. Zuniga, D. Katsavelis, J. Peck, J. Stollberg, M. Petrykowski, A. Carson, and C. Fernandez, "Cyborg beast: a low-cost 3d-printed prosthetic hand for children with upper-limb differences," *BMC research notes*, vol. 8, no. 1, p. 10, 2015.

[12] N. Herbert, D. Simpson, W. D. Spence, and W. Ion, "A preliminary investigation into the development of 3-d printing of prosthetic sockets," *Journal of rehabilitation research and development*, vol. 42, no. 2, p. 141, 2005.

[13] J. He, D. Li, B. Lu, Z. Wang, and T. Zhang, "Custom fabrication of a composite hemi-knee joint based on rapid prototyping," *Rapid prototyping journal*, vol. 12, no. 4, pp. 198–205, 2006.

[14] D. M. Sengeh and H. Herr, "A variable-impedance prosthetic socket for a transtibial amputee designed from magnetic resonance imaging data," *JPO: Journal of Prosthetics and Orthotics*, vol. 25, no. 3, pp. 129–137, 2013.

[15] T. Ramakrishnan, M. Schlafly, and K. Reed, "Biomimetic transfemoral knee with gear mesh locking mechanism," *International Journal of Engineering Research & Innovation*, 2017.

[16] R. Siebold, J. Axe, J. J. Irrgang, K. Li, S. Tashman, and F. H. Fu, "A computerized analysis of femoral condyle radii in acl intact and contralateral acl reconstructed knees using 3d ct," *Knee surgery, sports traumatology, arthroscopy*, vol. 18, no. 1, pp. 26–31, 2010.

[17] D. Siu, J. Rudan, H. Wevers, and P. Griffiths, "Femoral articular shape and geometry: a three-dimensional computerized analysis of the knee," *The Journal of arthroplasty*, vol. 11, no. 2, pp. 166–173, 1996.

[18] B. Yue, K. M. Varadarajan, S. Ai, T. Tang, H. E. Rubash, and G. Li, "Gender differences in the knees of chinese population," *Knee surgery, sports traumatology, arthroscopy*, vol. 19, no. 1, pp. 80–88, 2011.

[19] A. Monk, K. Choji, J. OConnor, J. Goodfellow, and D. Murray, "The shape of the distal femur," *Bone Joint J*, vol. 96, no. 12, pp. 1623–1630, 2014.

[20] T. Ramakrishnan, H. Muratagic, and K. B. Reed, "Combined gait asymmetry metric," in *38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2016.

[21] P. C. Mahalanobis, "On the generalized distance in statistics," *Proceedings of the National Institute of Sciences (Calcutta)*, vol. 2, pp. 49–55, 1936.

[22] H. E. Ross, "When is a weight not illusory?" *The Quarterly journal of experimental psychology*, vol. 21, no. 4, pp. 346–355, 1969.

[23] G. Buckingham, E. E. Michelakakis, and J. Cole, "Perceiving and acting upon weight illusions in the absence of somatosensory information," *Journal of neurophysiology*, vol. 115, no. 4, pp. 1946–1953, 2016.