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SYSTEMS-LEVEL QUALITY IMPROVEMENT

Performance Evaluation of Jaipur Knee Joint through Kinematics and Kinetics Gait Symmetry with Unilateral Transfemoral Indian Amputees

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Abstract

Gait analysis is considered as the most systematic study of human motion. The analysis of gait includes visual and analytical perception of the individual, augmentation of various mechanical instrumentations for measuring movement of body, muscles activity and body mechanics. Past study focused on gait analysis of various animal locomotion and humans mainly on sports biomechanics. This paper aims to quantify the gait performance with Jaipur Knee, which is one of the most widely used prosthesis in Indian population. Gait data with Jaipur knee joint is not available till date. The proposed study targets to predict the performance of Jaipur knee joint in terms of gait symmetry with transfemoral Indian amputees. Gait symmetry may be the basis of recommendation of knee joint to prosthetic patients. This study used kinematics and kinetics parameters together to quantify the performance of Jaipur knee joint to evaluate gait symmetry. This research will be helpful for clinician to predict and further to prevent the degenerated musculoskeletal effects generally seen in unilateral transfemoral amputees.

Keywords Amputation · Gait analysis · Jaipur knee · Transfemoral · Prosthesis

Introduction

Human gait data is very helpful in the prediction and correction of body movement control while walking. In many areas like medical practices, physical fitness training programs, rehabilitation techniques and prosthesis performance, gait study has its significant scientific relevance and applications. Gait study is used for the assessment and treatment of the individual having deformity or inability to walk properly.

The gait analysis requires a specific hardware equipped laboratory consisting of several cameras placed in and around a human patient walkway. Various markers are placed at standard reference points of the body. The most commonly used places for reflective markers are on pelvis, hip, knee and ankle joints [1]. With the implantation of reflective markers on body, patient walks under the surveillance of infrared cameras. By these cameras, the walking images of the individuals are recorded using the. Which are connected to computer to calculate the trajectory of individual marker in 3-dimensional space. This model gives the movement study of each joints where ever markers are present.

To calculate gait pattern kinetics, floor mounted transducers, or floor platforms are used. These floor platforms measure the ground moments and forces with the center of pressure while walking. In literature, several studies and researches outcomes exist that demonstrate the significant contribution of gait analysis. Balzac et al. considered the gait analysis to be very important to evaluate the performance of a prosthesis [2, 3]. Also, the metrices discussed by Ramakrishnan et al. served as a significant tool to classify and distinguish between multiple asymmetric bi-pedal gaits [4].

Bhagwan Mahaveer Viklang Sahayta Samiti (BMVSS), India, the initiators and developers of 'Jaipur foot' and Stanford University, USA, joined together and developed the Jaipur knee joint in year 2009. The Jaipur knee was recognized as one of the top 50 best inventions by Times magazine [5]. BMVSS, a non-profitable Indian organization, has successfully fitted more than 9000 knee joints through its free of cost license. The transfemoral prosthesis with Jaipur knee joint was fitted to thousands of Indians. This knee joint resulted an improved quality of life and amputees' mobility which resulted their better self-reliance and less stigma. That is why Jaipur knee

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joint's performance was evaluated with kinematic and kinetics symmetry indices. For unilateral transfemoral amputees, knee unit plays an important role as a critical component of prosthesis. This study may help clinicians to recommended suitable knee joint based on gait symmetry [6].

The basic purpose of prosthetic devices is to re-establish the functionality and utility of natural biological systems. It is very challenging for transfemoral amputees to walk normally due to their dependency on prosthesis to support total body weight. The gait symmetry is disturbed when amputees use prosthesis post-surgery or trauma. The gait asymmetry is generally observed in case of unilateral transfemoral amputees [7].

But, if there is the non-uniform distribution of body load, this may result pain experienced at backbone as well as in natural leg [8, 9] and evolution of other musculoskeletal degenerative problems [10]. Because of this asymmetry driven changes, the performance of amputee is reduced. Many researchers reported that non-distributed body load causes changes in knee kinematics and in the early stages of osteoarthritis (OA). The knee joint in prosthesis has been key areas for many researchers in current scenario. Some studies compared angle parameters in knee and hip joints during the gait of transfemoral amputees and determined the effect of the particular knee joint used in symmetry. Jaroslav et al. [11] also compared pelvic movements in transfemoral amputees using different types of knee joints.

The asymmetry during gait may be defined as a relation of kinematics or kinetic data for right and left legs. Robinson measured the angular position and acceleration by using Fourier series to parameter the measurements obtained through accelerometers [12]. The gait asymmetry is assessed by symmetry index (SI) calculation, a ratio index (RI) or a symmetry angle (SA) [13]. All these indices are discussed in the context of single point in gait cycle and limit the final assessment. The variation among the data, noted in performance of both limbs, is gait asymmetry. This asymmetry has been discussed with the use of ANOVA, t-test, variance ratio, principal component analysis, correlation coefficients, coefficients of variation, root mean square (RMS) difference methods and cross-correlation techniques [14], [15]. Al-Fatafta et al. examined the test and re-test repeatability of knee joint kinematics and kinetics in the sagittal, frontal and transverse planes during stair climbing with measurement error calculation. He also estimated the knee kinematics obtained using multi optimization for four different knee joint models [16].

In this work, the main emphasis is on the evaluation of the gait parameters with Jaipur knee to quantify its performance. This quantification of gait asymmetry may help to compare other available knee joints. Kinematics and kinetics parameters are used to evaluate gait symmetry. Rest of the paper is classified as follows: "Proposed methodology" gives the detail description of the working methodology. The experimental results are given in "Experimental results" followed by the discussion of the proposed methodology and results in "Discussion". The last "Conclusion", presents the conclusion of the whole work.

Proposed methodology

Dataset

The experimental dataset consisted of the eleven unilateral transfemoral amputees consisting of 9 men and 2 women with an average age of 45 years, which in the range of 31-58 years. All patients were using prosthesis for long time with mean duration 0f 16 years in the specific range of 5-27 years. Participants were suggested to walk with their comfortable speed to investigate the gait function with six VICON cameras capturing 3D motion analytical system, known as Kinematics system. All the eleven participants were suffering from above knee amputation in one limb after a physical injury or trauma, with no comorbidity voluntarily involved in this study as shown in Table 1. On prior to study, a written consent letter was taken from all participants after proper explanation of the use of generated dataset for research work.

Every patient was used to wear prosthesis for many years. During the experiment, same patients were asked to wear their prostheses fitted with Jaipur knee joint for a certain acclimation period as per suggested by the clinician. The research was carried under the supervision of trained and skilled staff at gait lab. All the steps to be involved in this study were discussed with subjects. The experienced gait lab staff verified socket fit, overall fitment and alignment of prosthesis to ensure stability and comfort for the amputees. A complete physical check-up of all participants, was done based on their history and current data of back joints, hip joints, knee joint, and any prior disease or injury etc. This pre-assessment of experienced clinician was to ensure that no related issues existed which may have altered their walking pattern.

Design study

In this study, a set of repeated experiments are conducted with eleven participants. At each iterative step, several measurements are recorded exclusively only on knee joints. In the experiment, knee joint acted as only standalone variable. To remove non-uniformity due to other prosthetic parts like foot and shank, the suspension system and the socket remained steady. The mass and related properties for prosthetic leg remained same for both knee joints. During the dataset generation, all the experiments were conducted

Table 1 Participant details with above knee amputation in one leg (Abbreviation: PVD - Peripheral Vascular Disease; CA - Cancer)

Participants	Age (years)	Sex	Causes	Amputation (years)	Acclimation (weeks)
A	26	M	Trauma	12	12.4
B	44	M	Trauma	17	13.7
C	58	M	PVD	19	13.2
D	42	M	Trauma	15	14.9
E	38	F	Trauma	10	10.6
F	60	M	CA	29	14.9
G	39	M	Trauma	7	11.7
H	47	F	Trauma	13	12.5
I	35	M	PVD	14	10.5
J	66	M	Trauma	31	11.8
K	34	M	Trauma	9	32.4

twice to remove any biasing and noise limitation. In other words, each patient underwent twice in experiment phase and their data were collected twice. At the first trial, each participant walked in four rounds with the speed as per his convenience on 8 m pathway using prosthesis with Jaipur knee. During this trial, average speed was recorded 1.11m/s (SD = 0.22 m/s). Thus, all subjects completed the necessary requirements of this study with Jaipur knee joints in prosthesis as expected.

Fitting and alignment of prosthesis

Alignment of prosthesis is to ensure amputee's stability and comfort, to check interlinked connection and orientation of different parts of above knee prosthesis. Improper alignment may result in uncomfortable fit and non-uniform pressure distribution on socket- limb joint boundary. Moreover it may lead to reduced comfort, uneasiness and potential tissue injury [17]. Besides this, misalignment in prosthesis component may cause difficult flexion or reduce knee stability. To avoid above consequences during the experiment, a trained and skilled gait laboratory staff carried out fitting and alignment of prosthesis at every stage.

Gait analysis

For kinematic evaluation, data are recorded with the help of computerized video motion analysis system which included six VICON cameras, with frame rate of 60 frames per seconds (fps) and using infrared (IR) light-emitting diode strobes. The cameras were located to yield accurate movement data of prominent joints like hip joints, knee joint and ankle joint for both legs in sagittal plane. The reflective markers were located at prominent bony locations to setup anatomic coordinate system as prescribed by clinician for gait test. Then movement data of both legs were recorded and processed by the motion capture system. During each trial, first static data was recorded when participant was standing comfortably. This data supported in calculations of joint centers positions. A strain-gauzed AMTI force plate dimensions (508 mm x 460 mm), was fitted in the middle position of defined pathway, measured data for ground reaction forces. The force plate data was synchronized to the computer system. The data received, from marker coordinate system and from AMTI force plate, were acted as input to calculate kinematics and kinetics parameters. Two consecutive heel strike positions were considered as gait cycle. Intermediate states of gait, were represented as percentage of total distance during gait.

Symmetry index

The kinetics and kinematics performance of knee joint in comparison with intact leg was measured with symmetry index. The symmetry index was calculated for both phases of gait cycle like first, when foot was in contact with ground and later when foot was in swing position. The main idea to calculate symmetry was to evaluate notable distinctions through quantitative approach between both legs during gait like Robinson adopted algebraic method to calculate symmetry index [18].

$$SI = \frac{2(X_{\mathrm{R}} - X_{\mathrm{L}})}{X_{\mathrm{R}} + X_{\mathrm{L}}} * 100 \quad (1)$$

Where, X_R and X_L are gait variables for both right and left leg respectively.

Ideally symmetry index should be equal to zero, when calculated all gait variables on discrete level. The approach used in this study was reported by Crankshaw [19] where the author utilized the Singular Value Decomposition (SVD) method. As acquired data was in a waveform thus all the variables got subtracted from its average value and translated accordingly. The resultant new data point was calculated as '2xn' matrix 'M'. Eigen values along with

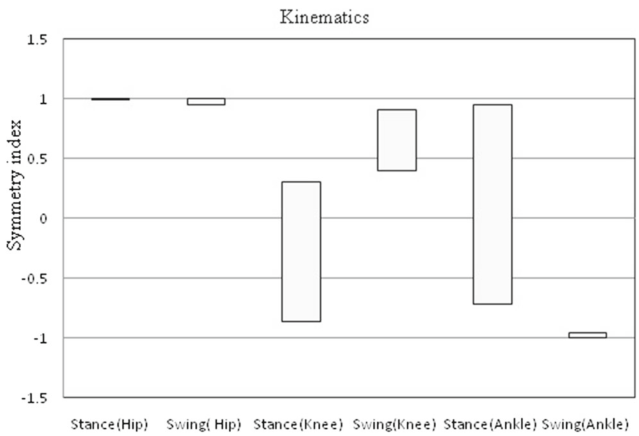

Fig. 1 Kinematics symmetry index for joints (hip, knee, ankle) resulted from Jaipur knee joint recorded in sagittal plane

Eigen vectors were determined from the matrix 'M'. In graph, '0' value indicates that the waveform was not affected while '+1' and '-1' donates the points of model symmetry and model asymmetry respectively. This data acquisition was done for both legs with kinetics and kinematic analysis is performed for hip joint, knee joint and ankle joints.

Statistical analysis

The movements of joint were captured in sagittal plane. As discussed in previously sub-sections that two gait phases with one knee joints were recorded in many trials therefore two-way analysis of variance (ANOVA) approach was preferred to measure deviation of symmetry while using two different knee joints units in prosthesis. Statistical significance was considered at $p \leq 0.05$.

Experimental results

Kinematic symmetry

The symmetry with kinematic data is found different for gait phase and joint level as shown in Fig. 1. The joint movements have recorded in sagittal plane, it is evident that appreciable symmetry is shown in swing phase as well as in stance phase of gait cycle. The sagittal motion exhibited good symmetry both in instance and swing phases where the symmetry index was more than 0.90 at hip joint in the amputee population, standard significance was set at $p = 0.14$. At the knee joint, notable symmetry deviation was seen during swing phase and stance phase at $p = 0.006$ which indicates maximum deviation in stance phase of knee joint. There is least symmetry reported during stance phase on changing knee locations with respect to loading conditions. On contrary to many participants justified kinematics symmetry during swing phase at $p = 0.36$. Likewise, at hip joint and ankle joint also, appreciable symmetry was reported in swing and stance phase. Data reported maximum asymmetry in graph indexed near to -1. In above knee prosthesis foot unit experiences less, planter flexion than intact leg that causes maximum asymmetry at ankle joint in swing phase. The data from a representative subject may justify logically the visible in symmetry obtained in Jaipur knee as shown in Fig. 2. The estimated symmetry index for joints i.e. hip, knee, and ankle for a representative participant in sagittal plane as shown in

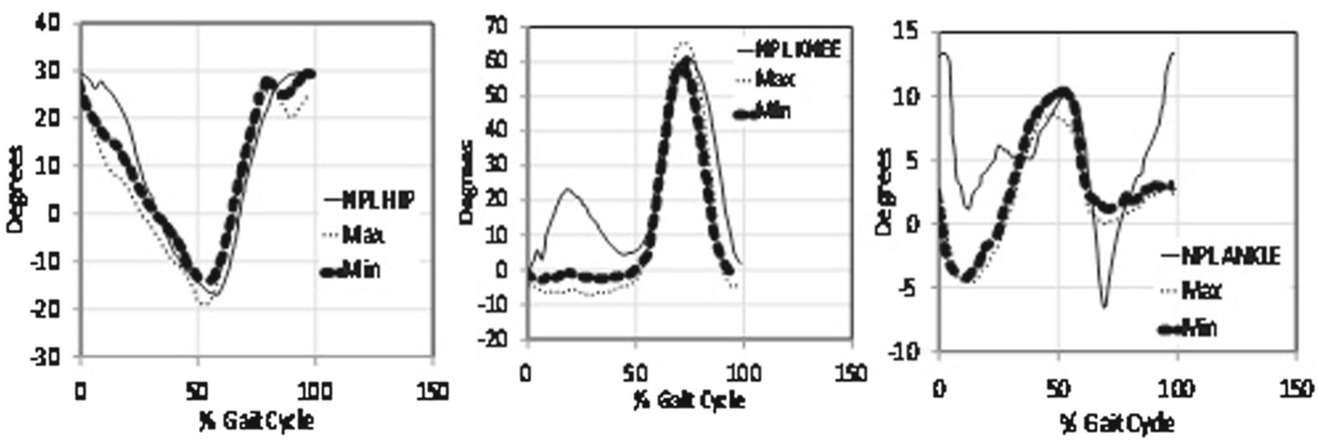

Fig. 2 Kinematics results in sagittal plane indicating three joints (hip, knee, ankle) for Non prosthetic leg leg- NPL (solid line) versus the prosthetic leg (dashed line) of a representative participant. The participants were using a Jaipur knee joint. Graph plots are as percentage of Gait cycle (% gait cycle), where 0% and 100% represent subsequent heel strike. Hip flexion, knee flexion and ankle dorsiflexion are indicated by positive values

Table 2 Estimated symmetry index for joints (hip, knee, ankle) for a representative participant in sagittal plane (as shown in Fig. 2)

Hip				Knee				Ankle			
Stance		Swing		Stance		Swing		Stance		Swing	
Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
0.996	0.989	0.991	0.985	0.356	-0.01	0.947	0.952	0.711	0.748	-0.99	0.991

Here +1 represents perfect symmetry and -1 as perfect asymmetry

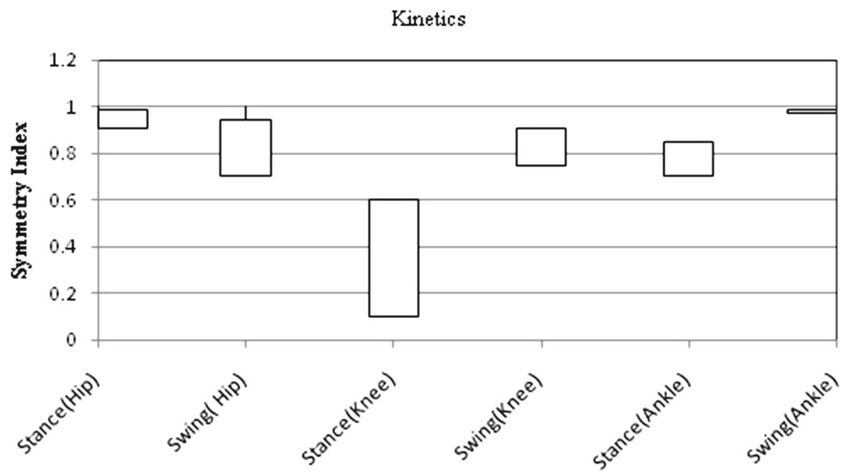

Fig. 3 Kinetics symmetry index for joints (hip, knee, ankle) resulted from Jaipur knee joints recorded in sagittal plane. Appreciable enhancement in the index for joints (hip, knee, ankle) with this joint. Notable variation of gait symmetry may be seen in stance and swing phases of participants

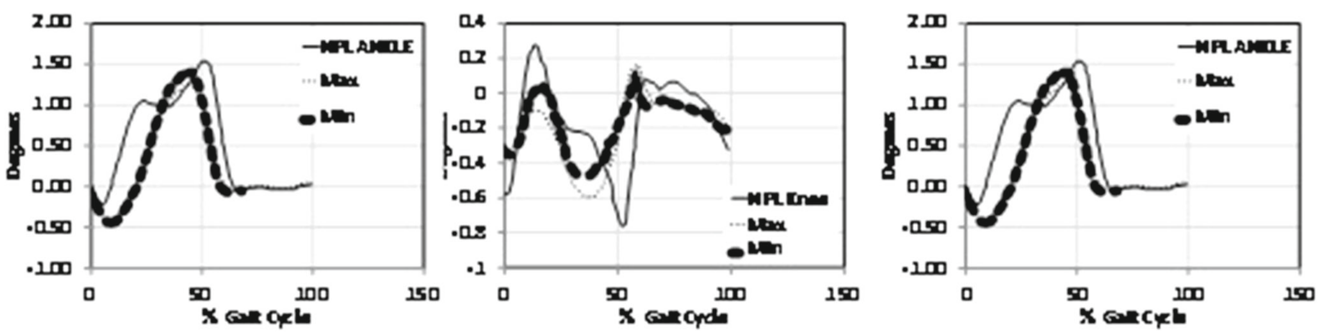

Fig. 4 Kinetics results in sagittal plane indicating three joints (hip, knee, ankle) for Non prosthetic leg- NPL (solid line) versus the prosthetic leg (dashed line) of a representative participant. The participant was using Jaipur knee joint. Graph plots are as percentage of Gait cycle (% gait cycle), where 0% and 100 % represent subsequent heel strike. Internal hip extensor, knee extensor and ankle planter flexor moment are indicated by positive values

Table 3 Estimated symmetry index for joints (hip, knee, ankle) for a representative participant in sagittal plane (shown in Fig. 4)

Hip				Knee				Ankle			
Stance		Swing		Stance		Swing		Stance		Swing	
Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
0.970	0.939	0.938	0.835	0.612	0.443	0.895	0.674	0.895	0.815	0.975	0.961

Here +1 represents perfect symmetry and -1 as perfect asymmetry

Fig. 2 is indexed in Table 2. The participants reported increased knee flexion against loading during gait, this response appreciably got compensated. That is why knee joint deviation in stance reported significant i.e., - 0.012.

Kinetic symmetry

With the use of experiment results, received from both trials it can be figured out that the symmetry observed at all joints are near to +1 and only exception was knee joint as shown in Fig. 3.

The hip joint reported maximum symmetry in stance phase in comparison to swing phase i.e., p = 0.075. On the other hand, maximum knee moment and ankle moment were appreciably more in swing phase than that of at stance phase at p = 0.0095. Each participant exhibited visible performance at all joint moments (hip, knee and ankle joint) in terms of kinetic symmetry with the use of Jaipur knee joint. As shown in Fig. 4, how kinetic symmetry is visible significantly with Jaipur knee joint. When Jaipur knee was used, knee moment got resulted in internal flexion zone in stance phase with symmetry index as 0.455. The estimated symmetry index for joints (hip, knee, ankle) for a representative participant in sagittal plane of data shown in Fig. 4 is indicated in Table 3.

Discussion

Main objective of this research is to evaluate and quantify the performance of Jaipur knee joint with the symmetry of gait cycle. For this, eleven participants used above knee prosthesis with Jaipur knee joint. To compare with ease, a healthy person's gait cycle was assumed as perfect symmetry. To compare the performance of knee joints Kauffman's technique was adopted. Kauffman did not only compare the points parallel to gait cycle but also utilized complete wave-front geometry [20]. The analysis concluded that participants exhibited better symmetrical gait from kinetic data with Jaipur knee joint. The outcome indicated almost similar kinematics profiles at joints (hip, knee and ankle) with Jaipur knee joint. Moreover, maximum flexion range at knee joint observed with better reduction in swing phase with Jaipur knee joints. When foot rests on ground during walk, knee joint ensures stability hence visibly enhanced moment at knee joint is clinically very significant. The outcome of research supports the fact that Jaipur knee joint enhances the symmetry during gait as compared to intact leg and this will ensure better balance and sound stability.

Besides this, few limitations are comprised with this study: first limitation is the testing orders in prosthesis which are not random. Participants first used prosthesis with different knee joints then they were asked to wear prosthesis with Jaipur knee joints. It may be considered conventional clinical context for the amputees on Jaipur joint. Second limitation may be participants' walking speed which was as per their comfort and were different with that of one another. Lela's et al. [21] discussed that different walking speeds may result in according differences in data used to calculate kinetics and kinematics related to walking speed. Likewise, Nolan et al. [22] concluded the effects seen in gait symmetry of participants due to different walking speed. Our result might have affected due to change in walking speed but in this study the variation of walking speeds is very small (approximate 0.06 m/s) and such small gap will not considerably affect the results of this study.

Conclusion

On the basis of outcome of this research, it may be concluded that unilateral tranfemoral amputees demonstrated appreciably reduced asymmetry with Jaipur knee joint. This conclusion quantified and measured differences between prosthetic leg and intact leg. This study will be useful for clinicians to predict the responses and performances of the different prosthetic knee joints. Quantification of gait symmetry and gait parameters will also be useful for the amputees to select and compare the available knee joints. This will avoid future disorders due to poor performance of the knee joint.

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Compliance with Ethical Standards

Conflict of interests The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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References

1. Hodgins, D., The importance of measuring human gait. *Med. Device Technol.* 19(5):44–47, 2008.
2. Balzac, H. D., *Theorie de la Demarche*. Paris: Didier, 1853.
3. Collado Vazqueza, S., and Carrillo, J., Balzac and human gait analysis. *Neurologia* 30(4):240–246, 2015.
4. Tamakrishnan, T., Lahiff, C., and Reed, K. B., Comparing gait with multiple physical asymmetries using consolidated metrices. *Frontoers in Nerorobotics* 12(2):1–12, 2018.
5. Inc., T. M., Time Megazine, 2009. http://content.time.com/time/specials/packages/article/00.html, [Accessed 31/05/2018].
6. jaipurfoot.org, Bhagwan Mahavir Sahayta Samiti, Jaipur, 2016. http://jaipurfoot.org. [Accessed 31 May 2018].
7. Jaegers, S. M. H. J., Arendzen, J. H., and De Jongh, H. J., The prosthetic gait of unilateral transfemoral amputees: a kinematic study. 76(8):736–43, 1995.
8. Bautmans, I., Jansen, B., Van Keymolen, B., and Mets, T., Reliability and clinical correlates of 3D-accelerometry based gait analysis outcomes according to age and fall-risk. *Gait Posture* 33(3):366–72, 2011.
9. Kulkarni, J., Adams, J., Thomas, E., and Silman, A., Association between amputation, arthritis and osteopenia in british male war veterans with major lower limb amputations. *Clin. Rehabil.* 12:348–353, 1998.
10. Johansson, J., Sherrill, D., Riley, P., Bonato, P., and Herr, H., A clinical coparison of variable damping and mechanically passive prosthetic knee devices. *Am. J. Phys. Med. Rehabil.* 84:563–575, 2005.
11. Jaroslav, U., Jandacka, D., Farana, R., Zahradnik, D., Rosicky, J., and Janura, M., Kinematics of gait using bionic and hydraulic knee joints in transfemoral amputees. *Acta Gymnica* 47(3):130–137, 2017.
12. Robinson, R., Herzog, W., and Nigg, B., Use of force plateform variables to quantify the effects of chiropractic manipulation on gait symmetry. *Manipulative Physiotherapy* 10:172–176, 1987.
13. Zifchock, R., Davis, I., and Higginson, J. R. T., Asymmetry angle: a novel, robust method of quantifying asymmetry. *Gait Posture* 27:622–627, 2008.
14. Sadeghi, H., Local or global asymmetry in gait of people without impairments. *Gait Posture* 17:197–204, 2003.
15. Haddad, J., Van Emmerik, R., Whittlesey, S., and Hamill, J., Adaptions in interlimb and intralimb coordination to asymmetrical loading in human walking. *Gait Posture* 23:429–434, 2006.
16. Al-Fatafta, H., Liu, A., Hutchins, S., and Jones, R., Knee joint kinematics and kinetics during the force plate attachable interlaced stairway climbing (FPAIS) in healthy individuals. Prosthetics and Orthotics Open Journal:1–15, 2017.
17. Yang, L., Solomonidis, S., and Spence, W. P. J., The influence of limb alignment on the gait of above knee amputees. *J. Biomech.* 24:981–997, 1991.
18. Blumentritt, S., A new biomechanical method for determination of static prosthetic alignment. *Prosthetics Orthot. Int.* 21:107–113, 1997.
19. Crenshaw, S., and Richards, J., A method for analyzing joint symmetry abnormally with an applications to analyzing gait. *Gait Posture* 24:515–521, 2006.
20. Kaufman, K., Levine, J., Brey, R., Mccrady, S., Padgett, D., and Joyner, M., Energy expenditure and activity of transfemoral amputees using mechanical and microprocesssor controlled prosthetic knees. *Arch. Phys. Med. Rehabil.* 87:1382–1385, 2008.
21. Lelas, J., Merriman, G., Riley, P., and Kerrigan, D., Predicting peak kinematic and kinetic parameters from gait speed. *Gait Posture* 17:106–112, 2003.
22. Nolan, L., Wit, A., Dudzinski, K., Lees, A., Lake, M., and Wychowansky, M., Adjustments in gait symmetry with walking speed in transfemoral and trandtibial amputees. *Gait Posture* 17:142–151, 2003.

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