Crowd-sourced amputee gait data: a feasibility study using YouTube videos of unilateral trans-femoral gait

Gardiner, JD, Gunarathne, N, Howard, D and Kenney, LPJ

http://dx.doi.org/10.1371/journal.pone.0165287

| Title                                      | Crowd-sourced amputee gait data: a feasibility study using YouTube videos of unilateral trans-femoral gait |
|--------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Authors                                    | Gardiner, JD, Gunarathne, N, Howard, D and Kenney, LPJ                                                    |
| Type                                       | Article                                                                                                  |
| URL                                        | This version is available at: http://usir.salford.ac.uk/40367/                                           |
| Published Date                             | 2016                                                                                                     |

USIR is a digital collection of the research output of the University of Salford. Where copyright permits, full text material held in the repository is made freely available online and can be read, downloaded and copied for non-commercial private study or research purposes. Please check the manuscript for any further copyright restrictions.

For more information, including our policy and submission procedure, please contact the Repository Team at: usir@salford.ac.uk.
Crowd-Sourced Amputee Gait Data: A Feasibility Study Using YouTube Videos of Unilateral Trans-Femoral Gait

James Gardiner¹*, Nuwan Gunarathne², David Howard¹, Laurence Kenney²

¹ School of Computing, Science and Engineering, University of Salford, Salford, United Kingdom, ² School of Health Sciences, University of Salford, Salford, United Kingdom

* j.d.gardiner@salford.ac.uk

Abstract

Collecting large datasets of amputee gait data is notoriously difficult. Additionally, collecting data on less prevalent amputations or on gait activities other than level walking and running on hard surfaces is rarely attempted. However, with the wealth of user-generated content on the Internet, the scope for collecting amputee gait data from alternative sources other than traditional gait labs is intriguing. Here we investigate the potential of YouTube videos to provide gait data on amputee walking. We use an example dataset of trans-femoral amputees level walking at self-selected speeds to collect temporal gait parameters and calculate gait asymmetry. We compare our YouTube data with typical literature values, and show that our methodology produces results that are highly comparable to data collected in a traditional manner. The similarity between the results of our novel methodology and literature values lends confidence to our technique. Nevertheless, clear challenges with the collection and interpretation of crowd-sourced gait data remain, including long term access to datasets, and a lack of validity and reliability studies in this area.

Introduction

Collecting large datasets of amputee gait is notoriously difficult. Especially, for less prevalent amputation levels and for elderly vascular amputees (aged over 65), the largest and most challenging to rehabilitate section of the amputee population [1]. Indeed, due to the practicalities of collecting kinematic and kinetic data many studies of amputee gait performance are conducted in highly controlled laboratory environment and include small numbers of subjects. For example Hofstad et al.’s Cochrane review [2] of prosthetic ankle/feet joints includes 26 studies, with an average of just over 9 patients per study, with only 5 studies including more than 10 participants. Additionally, although a few recent studies have begun to explore amputee walking on surfaces representative of the everyday environment [3–7] many, if not most, amputee gait studies are conducted in gait laboratories, which greatly limits the extent to which results can be generalised. This is especially important, since walking in the community involves many surfaces that are not level, smooth or flat, for example, stairs, ramps, gravel paths, grass
etc. Nevertheless, the gait laboratory approach has provided detailed insights into the relationships between prosthesis properties, amputee characteristics and gait, and will of course continue to play a central role in research for the foreseeable future. However, larger datasets on the performance of subjects with more unusual amputation levels and/or challenging pathologies, and datasets on conditions outside of typical lab environments are scarcer in current literature and remain difficult to collect. In this manuscript we investigate the potential of ‘crowd-source’ video footage as a source of amputee gait data to help address these issues, and provide substantial datasets of high quality amputee gait data.

Crowd-sourcing is the idea of outsourcing data collection/processing to the general public and has been gaining popularity in the scientific community. Indeed, several high profile studies have caught the public imagination [8] such as protein folding game ‘foldit’ and galaxy classification website ‘galaxy zoo’. These projects, however, require active participation from members of the public. There is also a wealth of user generated content on the Internet that requires no further input from the public and is potentially a valuable source of data for researchers. Indeed, many websites exist solely to promote user-generated content, such as photos, music and videos. YouTube in particular has been used as a tool to study a variety of medical topics such as kidney stones [9], cardiopulmonary resuscitation [10] and Human Papillomavirus (HPV) vaccination [11].

Many amputees post videos of themselves using their prosthesis in a variety of scenarios, such as running, walking and stair climbing. However, as far the authors are aware the potential of these crowd-sourced videos for amputee gait analysis has yet to be acknowledged or tested. Here we investigate the potential of user-generated videos (from websites such as YouTube) to provide temporal gait parameters for amputees using their prosthetic devices. To allow for validation of our results against existing literature, we focus our analysis on an example dataset of unilateral trans-femoral amputees level walking at a self-selected speed and compare our data against published values.

**Materials and Methods**

The video sharing website YouTube (www.youtube.com) was searched for videos of trans-femoral amputee gait. The searches of YouTube’s database were conducted between the 18\textsuperscript{th} of February and the 31\textsuperscript{st} March 2015 by a single researcher (N.G.). The website was queried using the following terms in a variety of combinations: amputee, walking, prosthetics, gait, trans-femoral. Only the first page of search results (typically 20 results per page) was checked for videos, due to that fact that any search in YouTube typically produces tens of thousands of results. Videos that contained clear footage of adult unilateral trans-femoral amputee walking on level ground were downloaded for further analysis, regardless of language. Videos were only selected for analysis where both legs were clearly visible and walking was in a straight line at a consistent walking speed for a minimum of five complete gait cycles. Both company promotional videos and individual amputee’s own videos were included. Videos that clearly contained early rehabilitation footage were rejected, since it was thought that these videos might skew the results. All data from the YouTube videos were anonymised and collected under the ‘Fair Use’ and ‘Exceptions to Copyright’ rules for non-commercial research. Please see: https://www.youtube.com/yt/copyright/en-GB/fair-use.html and https://www.gov.uk/guidance/exceptions-to-copyright.

The downloaded videos were analysed using Tracker 4.87 (OpenSourcePhysics), which allows the user to process the YouTube footage frame by frame. Therefore, the timings of frames in which the heel first visibly touched the ground were recorded as the heel strikes. Likewise the timings of the video frames in which the toe first visibly left the ground were...
recorded as toe-off. This process was repeated for both legs for five complete gait cycles and
the collected data was used to calculate the gait cycle time, and also the swing and stance
times for both the prosthetic and sound leg. The five complete gait cycles were averaged to
give mean values of these temporal parameters. This temporal data was then used to calculate
the duty factors (i.e. stance phase as a percentage of the gait cycle) for the prosthetic and
sound leg. To test whether the data we gathered was significantly asymmetric, a commonly
used gait asymmetry index \[12–15\] was calculated from the stance phase data using the fol-

\[
A = \frac{S_i - S_p}{\frac{1}{2}(S_i + S_p)}
\]

where \(A\) is asymmetry index, \(S_i\) is intact stance phase duration and \(S_p\) is prosthetic stance
phase duration. The asymmetry index was tested using a two way \(t\)-test with an asymmetry
index of zero being the null hypothesis representing perfectly symmetrical gait.

Our temporal amputee gait data was then compared with existing data from the literature
\[14–18\] to assess the variability of our data, and hence the feasibility of our methodology for
future research studies. We assumed that all the studies (our research and the literature)
draw from the same overall population of unilateral trans-femoral amputees and therefore
conducted an ANOVA on the results to test for significant differences between studies. A
Tukey-Kramer post hoc test was conducted to identify which studies were significantly differ-
ent. The ANOVA and Tukey-Kramer post hoc were performed using MATLAB\textsuperscript{R}\textsuperscript{2014b}
with the statistics toolbox (The MathWorks, Inc., Natick, Massachusetts, United States). The
study of van der Linden et al. \[18\] only included detailed results for a single amputee, there-
fore was not included in the ANOVA and was only included in the figures for visual
reference.

**Results**

Sixteen videos of adult unilateral trans-femoral level walking were downloaded from YouTube
and used for further analysis. The detail of the study population can be seen in Table 1. Twelve
of the videos contained footage of men walking and four of women. The majority of videos
were of young or middle aged amputees using Ottobock Genium or C-legs, in trainers.

The results for gait cycle time, stance times, stance duty factors and asymmetry index can be
seen in Table 2 and Figs 1 and 2. The mean asymmetry index (0.104), was significantly different
from the null hypothesis of zero, \(t(15) = 4.55, p<0.001\).

We used an ANOVA to compare the results of our study with data from the literature, and
found some significant difference between studies (Table 3). No significant differences were
found between prosthetic stance times (\(F(4,59) = 2.13, p = 0.088\)), intact stance phases (\(F(4,59) =
1.07, p = 0.381\)) or asymmetry indices (\(F(4,59) = 1.68, p = 0.167\)) from all studies. However, sig-
nificant difference for intact stance time (\(F(4,59) = 6.92, p = 0.0001\)), gait cycle time (\(F(4,59) =
13.28 p < 0.0001\)) and prosthetic stance phase (\(F(4,59) = 2.86, p = 0.031\)) were found. Intact
stance time from our study was significantly different from the studies of Boonstra et al. \[17\] and
Nolan et al. \[15\]. No other differences in intact stance time were found. Gait cycle time for
our study was significantly different from studies of Jaegar et al. \[16\],Boonstra et al. \[17\] and
Nolan et al. \[15\] but not different from Schaarschmidt et al. \[14\]. Similarly, gait cycle time for
Schaarschmidt et al. \[14\] was significantly different from Jaegar et al. \[16\] and Boonstra et al.
\[17\]. No other differences in gait cycle time were found. Prosthetic stance phase for our study
was significantly different from Boonstra et al. \[17\].
Discussion

The use of crowd-sourced videos for temporal gait analysis in amputee locomotion has not yet been acknowledged or tested. Here we show that temporal gait data collected from YouTube videos of unilateral trans-femoral amputees is comparable and of equivalent variability to gait data published in the literature. Although we do not have access to synchronous gold standard measurements for error analysis purposes, this result lends confidence to our data collection methodology and demonstrates the potential for the future use of YouTube videos for gait data collection in general.

In this study our example dataset of temporal gait parameters for trans-femoral amputees are similar to values taken from published literature (Figs 1 and 2). Mean and standard deviation values for gait cycle time and stances times, for both intact and prosthetic side, are generally comparable to values previously published (Fig 1). Using an ANOVA differences were found for intact stance time, gait cycle time and prosthetic stance phase between some studies. The difference in gait cycle time are due to differences in cadence (steps per minute) between study subjects, which may relate to differences in walking speed (1.0 to 1.2 m/s for the cited studies included in the analysis). Differences in cadence and walking speed would also explain the difference in intact stance time and prosthetic stance phase. Difficulty in controlling (or

Table 1. Details of study population taken from the videos and associated online meta data.

| Video | Sex | Age | Amputation reason | Time since amputation (years) | Leg | Footwear |
|-------|-----|-----|-------------------|------------------------------|-----|----------|
| 1     | M   | Middle | Traumatic       | 8                            | Ottobock C-Leg | Trainers |
| 2     | M   | Young  | Unknown          | <1                           | Ottobock 3R80  | Trainers |
| 3     | F   | Middle | Traumatic       | 1                            | Ottobock Genium | Sandals |
| 4     | M   | Middle | Unknown          | Unknown                      | Ottobock C-Leg | Trainers |
| 5*    | M   | Unknown| Unknown          | Unknown                      | Non-microprocessor | Unknown |
| 6     | F   | Unclear| Unknown          | Unknown                      | Ottobock C-Leg | Trainers |
| 7     | M   | Young  | Unknown          | Unknown                      | Ottobock Genium | Trainers |
| 8     | M   | Unclear| Unknown          | Unknown                      | Ottobock Genium | Trainers |
| 9     | M   | Young  | Unknown          | Unknown                      | Ottobock Genium | Trainers |
| 10    | M   | Young  | Unknown          | Unknown                      | Ottobock Genium | Trainers |
| 11    | F   | Middle | Bone cancer      | >35                          | Ottobock C-Leg | Shoes    |
| 12    | M   | Young  | Unknown          | Unknown                      | Ottobock C-Leg | Trainers |
| 13    | M   | Young  | Congenital disorder | 6                           | Ottobock C-Leg | Trainers |
| 14    | M   | Young  | Unknown          | Unknown                      | Ottobock Genium | Trainers |
| 15    | M   | Young  | Unknown          | Unknown                      | Ottobock C-Leg | Trainers |
| 16    | F   | Young  | Traumatic        | >3                          | Unknown              | Shoes/Trainers |

* Video 5 was no longer online to allow additional information to be collected for the details of study population (suggestion by draft manuscript reviewer). Therefore only limited information was recorded for this video and this issue highlights the transient nature of data sources such as YouTube.

doi:10.1371/journal.pone.0165287.t001

Table 2. Temporal gait parameters of YouTube trans-femoral amputees level walking at self-selected speed.

|                  | Gait cycle time (s) | Intact stance time (s) | Intact stance duty factor (%) | Prosthetic stance time (s) | Prosthetic stance duty factor (%) | Asymmetry index |
|------------------|---------------------|------------------------|-----------------------------|---------------------------|----------------------------------|----------------|
| Mean             | 1.161               | 0.765                  | 65.8                        | 0.694                     | 59.4                             | 0.104          |
| SD               | 0.111               | 0.111                  | 3.3                         | 0.093                     | 5.0                              | 0.091          |

Subjects were adult unilateral trans-femoral amputees walking on a level surface at a self-selected speed. Means and standard deviations were calculated for the sample of 16 subjects.

doi:10.1371/journal.pone.0165287.t002
indeed measuring) variables such as walking speed from YouTube videos is an inherent drawback of our methodology and one which needs careful consideration before embarking on studies using internet videos. Nevertheless, the similarity of our results with other published studies was surprising since we suspected that both the data collection protocol (i.e. digitising videos recorded on standard video cameras) and the uncontrolled nature of the video content (i.e. prosthesis type, gender, age etc.) may have led to an increase in the variability of the results. However, it appears that the data collection method used here produces results of a comparable variability to studies carried out under highly controlled conditions using laboratory-standard data collection tools. This suggests that either the inherent ‘noisiness’ of trans-femoral gait data is larger than the variability resulting from the differences between prosthesis types, ages etc. seen in our videos, or that in level walking trans-femoral amputees in the ‘real’ world are similar to those walking in gait labs.

The data from our YouTube study lends confidence to our methodology and suggests that the scope could be expanded in future studies. Indeed, as markerless gait analysis techniques improve (for example [19,20,21]) the potential scope for the types of data that could be collected from internet videos should increase beyond just the temporal parameters illustrated here. Furthermore whilst searching for trans-femoral walking videos for this study the number, variety and scope of potential videos found on YouTube was exceptional with many videos.
Fig 2. Stance phase and asymmetry index of trans-femoral amputees level walking at self-selected speed. Top: Stance phase (also known as duty factor) for both intact and prosthetic leg of unilateral trans-femoral amputees level walking at self-selected speeds. Our study results are consistent with those found in the literature with the stance phase on the prosthetic leg being consistently shorter than the intact leg. Bottom: The asymmetry index calculated from stance phase data. Our study (and literature studies) show significant asymmetry of gait for the amputees (no asymmetry would equal 0). All bars display means with standard deviation error bars. The study of van der Linden et al [18] only includes data for a single amputee, hence the lack error bars.

doi:10.1371/journal.pone.0165287.g002
showing gait activities that are not normally studied, for example videos of amputees walking on rough and loose terrain. Amputee gait data for walking on anything other than flat and firm surfaces are generally quite rare in the literature, and researchers could make use of these videos to compare and contrast gait on a variety of terrains. Indeed, there are even videos of more ‘extreme’ activities such as rock climbing, snowboarding and amputee soccer, which researchers in para-sports and para-athletics may find valuable for their studies. In addition to the variety of walking surfaces and activities found in the videos, there are also videos from subjects with less prevalent amputations, such as bi-lateral trans-femoral amputations, conditions for which conventional studies are inevitably limited in terms of sample size.

Having discussed the potential merits of crowd-sourced data it is necessary to also address the significant limitations with the approach, which should be considered before future researchers engage in these types of studies. Firstly, the search strategy was limited in scope. However, it did identify a number of relevant videos, sufficient to demonstrate the feasibility of the approach. It is also interesting to note that since YouTube videos do not require the user to input structured descriptors, it remains unclear whether a significantly improved approach could be implemented and this may remain a significant limitation with the approach as presented in our paper. Furthermore YouTube videos can be uploaded or deleted by users at will (see Table 1 and video 5 of our study) and hence ensuring the repeatability of the work presents a challenge. One option which could be explored would be to make copies of the relevant videos and upload them to a more permanent location, using tools such as FigShare. However, IP, ethical and consent issues may present a major challenge to this. Secondly, considering the quality of the data, the videos are collected under typically uncontrolled lighting conditions with a range of different cameras and viewpoints. These factors might be expected to introduce error when digitising the data to derive useful parameters, such as step time and future studies may usefully consider quantifying the scale of these errors through repeatability and validity studies. For instance, the use of wearable sensors can provide “gold standard” temporal data “out of the lab” [22,23], which could be compared with data derived from video analysis. The approach, as presented in this paper, is also clearly limited by a lack of data on participants and their prosthetic components. Future studies may consider a more pro-active approach, as

| Table 3. Tukey-Kramer post hoc p values for intact leg stance times, gait cycle time and prosthetic stance phase. |
|---------------------------------------------------------------|
| Intact stance time | Schaarschmidt et al. 2012 | Jaeger et al. 1995 | Boonstra et al. 1996 | Nolan et al. 2003 |
|-------------------|---------------------------|-------------------|---------------------|-------------------|
| Our study         | 0.9948                    | 0.1146            | 0.0002*             | 0.0149*           |
| Schaarschmidt et al. 2012 | \                 | 0.6629            | 0.0837              | 0.1232            |
| Jaeger et al. 1995 | \                         | \                | 0.6264              | 0.5785            |
| Boonstra et al. 1996 | \                        | \                 | \                   | 0.9596            |
| Gait cycle time   | Schaarschmidt et al. 2012 | Jaeger et al. 1995 | Boonstra et al. 1996 | Nolan et al. 2003 |
|-------------------|---------------------------|-------------------|---------------------|-------------------|
| Our study         | 1                         | 0.0001*           | <0.0001*            | 0.0332*           |
| Schaarschmidt et al. 2012 | \                 | 0.0103*           | 0.0012*             | 0.1148            |
| Jaeger et al. 1995 | \                         | \                | 0.9918              | 0.9977            |
| Boonstra et al. 1996 | \                        | \                 | \                   | 0.9673            |
| Prosthetic stance phase | Schaarschmidt et al. 2012 | Jaeger et al. 1995 | Boonstra et al. 1996 | Nolan et al. 2003 |
|-------------------|---------------------------|-------------------|---------------------|-------------------|
| Our study         | 0.9999                    | 0.9948            | 0.0327*             | 0.8836            |
| Schaarschmidt et al. 2012 | \                 | 0.9999            | 0.4001              | 0.963             |
| Jaeger et al. 1995 | \                         | \                | 0.1968              | 0.9699            |
| Boonstra et al. 1996 | \                        | \                 | \                   | 0.9372            |

p value less than 0.05 indicates a significant difference between studies (indicated with a *)

doi:10.1371/journal.pone.0165287.t003
outlined below. Finally, it is clear that our approach could only provide limited temporal and kinematic data, even with the use of advanced image analysis tools. For research that requires more detailed data this approach is unlikely to be beneficial.

Nevertheless, the wealth of potential data available online makes the above challenges worth overcoming and we encourage this approaches consideration for future research. Indeed, both the breadth and number of amputee gait videos online is already remarkable and they are likely to continue to grow in coming years. Further, future studies could also consider taking an active ‘citizen science’ approach to data collection. For example, researchers could conduct ‘organised crowd-sourcing’ projects that ask patients with particular conditions to upload videos of themselves performing a protocol or activity. This idea could be extended from gait studies into a variety of functional tasks performed by patients. Conducting studies in this manner would help to negate some of the problems faced by current researchers, notably low statistical power. However, such an active approach would potentially create new problems in terms of co-ordination of projects, language barriers and recruitment of subjects. We encourage researchers of amputee gait to investigate the potential of our approach highlighted in this feasibility study and to also more clearly identify the scope of problems for which our technique may be suitable.

Conclusions

The growth of easily accessible gait data on the Internet should inspire researchers to conduct studies that might have been very difficult in the pre-internet age. We have shown here that collecting an example dataset of amputee temporal gait data from YouTube videos produces results that are comparable with published data from controlled laboratory studies. Therefore, the potential for future studies to make use of YouTube and other online resources for collecting data on amputee gait is large and we encourage other researchers to explore how best to use this resource.

Supporting Information

S1 File. Excel spreadsheet containing all data and figures used in this study. The collated data contains both the data from our YouTube video analysis and the data collected from the literature studies.

Acknowledgments

We would like to thank Dr Bill Sellers and Dr John Lees for their helpful discussions regarding this work.

Author Contributions

Conceptualization: JG DH LK.

Formal analysis: JG NG.

Funding acquisition: DH LK.

Methodology: JG NG.

Writing – original draft: JG NG DH LK.

Writing – review & editing: JG DH LK.
References

1. Fletcher DD, Andrews KL, Butters MA, Jacobsen SJ, Rowland CM, Hallett JW. Rehabilitation of the geriatric vascular amputee patient: A population-based study. Arch Phys Med Rehabil. 2001; 82:776–779. doi: 10.1053/apmr.2001.21866 PMID: 11387582

2. Hofstad C, Linde H, Limbeek J, Postema K. Prescription of prosthetic ankle-foot mechanisms after lower limb amputation. Cochrane database Syst Rev. 2004;CD003978. doi: 10.1002/14651858.CD003978.pub2 PMID: 14974050

3. Beurskens R, Wilken JM, Dingwell JB. Dynamic stability of superior vs. inferior body segments in individuals with transtibial amputation walking in destabilizing environments. J Biomech. Elsevier; 2014; 47:3072–3079. doi: 10.1016/j.jbiomech.2014.06.041 PMID: 25064425

4. Hak L, Van Dieën JH, Van Der Wurff P, Prins MR, Mert A, Beek PJ, et al. Walking in an unstable environment: Strategies used by transtibial amputees to prevent falling during gait. Arch Phys Med Rehabil. 2013; 94:2186–2193. doi: 10.1016/j.apmr.2013.07.020 PMID: 23916618

5. Starholm I-M, Gjovaa T, Mengshoel AM. Energy expenditure of transfemoral amputees walking on a horizontal and tilted treadmill simulating different outdoor walking conditions. Prosthet Orthot Int. 2010; 34:184–194. doi: 10.3109/03093640903585016 PMID: 20141493

6. Sup F, Varol H, Goldfarb M. Upslope Walking With a Powered Knee and Ankle Prosthesis: Initial Results With an Amputee Subject. IEEE Trans NEURAL Syst Rehabil Eng. 2011; 19:71–78. doi: 10.1109/TNSRE.2010.2087360 PMID: 2092344

7. Paysant J, Beyaert C, Dati A-M, Martinet N, Andr J-M. Influence of terrain on metabolic and temporal gait characteristics of unilateral transtibial amputees. J Rehabil Res Dev. 2006; 43:153. doi: 10.1682/JRRD.2005.02.0043 PMID: 16847782

8. Hand E. People power. Nature. 2010; 466:685–687. PMID: 20686547

9. Sood A, Sarangi S, Pandey A, Murugiah K. YouTube as a source of information on kidney stone disease. Urology. Elsevier Inc.; 2011; 77:558–562. doi: 10.1016/j.urology.2010.07.536 PMID: 21131027

10. Murugiah K, Vallakati A, Rajput K, Sood A, Challa NR. YouTube as a source of information on cardiopulmonary resuscitation. Resuscitation. 2011; 82:332–334. doi: 10.1016/j.resuscitation.2010.11.015 PMID: 21185643

11. Ache KA, Wallace LS. Human Papillomavirus Vaccination Coverage on YouTube. Am J Prev Med. 2008; 35:389–392. doi: 10.1016/j.amepre.2008.06.029 PMID: 18675530

12. Becker HP, Rosenbaum D, Kriese T, Gerngross H, Claes L. Gait asymmetry following successful surgical treatment of ankle fractures in young adults. Clin Orthop Relat Res. 1995;262–269.

13. Shorter KA, Polk JD, Rosengren KS, Hsiao-Weckslser ET. A new approach to detecting asymmetries in gait. Clin Biomech. 2008; 23:459–467. doi: 10.1016/j.clinbiomech.2007.11.009 PMID: 18242805

14. Schaarschmidt M, Lipfert SW, Meier-Gratz C, Scholle HC, Seyfarth A. Functional gait asymmetry of unilateral transfemoral amputees. Hum Mov Sci. Elsevier B.V.; 2012; 31:907–917. doi: 10.1016/j.humov.2011.09.004 PMID: 22248566

15. Nolan L, Wit A, Dudziński K, Lees A, Lake M, Wychowański M. Adjustments in gait symmetry with walking speed in transfemoral and transtibial amputees. Gait Posture. 2003; 17:142–151. doi: 10.1016/S0966-6362(02)00066-8 PMID: 12633775

16. Jaegers SMHJ, Arendzen JH, De Jongh HJ. Prosthetic gait of unilateral transfemoral amputees: A kinematic study. Arch Phys Med Rehabil. 1995; 76:736–743. doi: 10.1016/S0003-9993(95)80528-1 PMID: 7632129

17. Boonstra AM, Schrama JM, Eisma WH, Hof AL, Fidler V. Gait analysis of transfemoral amputee patients using prostheses with two different knee joints. Arch Phys Med Rehabil. 1996; 77:515–520. doi: 10.1016/S0003-9993(96)90044-1 PMID: 8629932

18. van der Linden ML, Solomonidis SE, Spence WD, Li N, Paul JP. A methodology for studying the effects of various types of prosthetic feet on the biomechanics of transfemoral amputee gait. J Biomech. 1999; 32:877–889. doi: 10.1016/S0021-9290(99)00086-X PMID: 10460124

19. Sandau M, Koblauch H, Moeslund TB, Aanes A, Alkjaer T, Simonsen EB. Markerless motion capture can provide reliable 3D gait kinematics in the sagittal and frontal plane. Med Eng Phys. Institute of Physics and Engineering in Medicine; 2014; 36:1168–1175. doi: 10.1016/j.medengphy.2014.07.007 PMID: 25085672

20. Ceseracciu E, Sawacha Z, Cobelli C. Comparison of markerless and marker-based motion capture technologies through simultaneous data collection during gait: Proof of concept. PLoS One. 2014; 9:1–7. doi: 10.1371/journal.pone.0087640 PMID: 24595273
21. Castelli A, Paolini G, Cereatti A, Della Croce U. A 2D Markerless Gait Analysis Methodology: Validation on Healthy Subjects. Comput Math Methods Med. 2015; 2015:186780. doi: 10.1155/2015/186780 PMID: 26064181

22. LeMoyne R. Future and advanced concepts for the powered prosthesis. Advances for prosthetic technology: from historical perspective to current status to future application. Springer; 2016. pp. 127–130.

23. Albert M V., McCarthy C, Valentin J, Herrmann M, Kording K, Jayaraman A. Monitoring Functional Capability of Individuals with Lower Limb Amputations Using Mobile Phones. PLoS One. 2013; 8:6–11. doi: 10.1371/journal.pone.0065340 PMID: 23750254