European Journal of Orthopaedic Surgery & Traumatology (2019) 29:683–687
https://doi.org/10.1007/s00590-018-2346-0

ORIGINAL ARTICLE • ANKLE - BIOMECHANICS

Relationships among subjective patient-reported outcome, quality of life, and objective gait characteristics using wearable foot inertial-sensor assessment in foot–ankle patients

Chayanin Angthong[1] · **Andrea Veljkovic**[2]

Received: 22 August 2018 / Accepted: 25 November 2018 / Published online: 28 November 2018

Abstract

Background This study aimed to determine the relationships between subjective validated patient-reported outcomes and health-related quality of life, to objective gait characteristics in patients with foot–ankle conditions. Objective gait characteristics were obtained using a wearable foot inertial-sensor device as well as by assessing the relationships between spatiotemporal or gait parameters by analyzing the inter-metric correlations.

Methods Fifty-two patients with foot–ankle conditions (37 women/15 men, aged 21–75 years) were included in this study. Clinical assessments, including evaluations of validated patient-reported outcomes using visual analog scale foot and ankle score, health-related quality of life using validated Short Form-36, and gait characteristics using a wearable foot inertial-sensor device, were performed and recorded for each patient.

Results A significant negative correlation was observed between the physical component summary (PCS) and maximal cadence ($r=-0.308$, $P=0.025$). Significant positive correlations were noted between mean walking speed and mean cadence ($r=0.776$, $P<0.001$) and between maximal walking speed and mean step length ($r=0.498$, $P<0.001$). Significant negative correlations were found between the mean cadence and mean step length ($r=-0.491$, $P<0.001$) and between maximal cadence and mean step length ($r=-0.355$, $P=0.009$).

Conclusions Cadence is an important objective spatiotemporal parameter to assess in foot and ankle patients as it relates well to outcome, with a significantly negatively correlation to subjectively reported PCS in health-related quality of life. Based on inter-metric relationships, an increased cadence might be used to maintain walking speed as a compensatory mechanism in patients with foot–ankle conditions.

Keywords Patient-reported outcome measures · Gait · Wearable electronic device · Foot and ankle pathology

Introduction

Evaluations of patients with foot and ankle conditions consist of subjective and objective assessments. However, occasional inconsistencies exist between patients' symptoms and the findings of objective measurements [1]. In addition, the combinations of objective and subjective assessments have not been adequately validated [2–4]. Currently, several studies have attempted to report the relationships between patient-reported outcomes and/or quality of life and objective measures, such as gait metrics [5–7]. However, no general consensus exists on the relationships between the spatiotemporal parameters in gait kinematic studies, such as the effects of walking speed change on other parameters in patients with foot and ankle conditions [6, 7].

The purpose of this study was to report the relationships among validated patient-reported outcomes [8], health-related quality of life [9], and gait characteristics using a wearable foot inertial-sensor device in patients with foot and ankle conditions. Moreover, the inter-metric correlations were also analyzed to determine the relationships between

✉ Chayanin Angthong
chatthara@yahoo.com

[1] Department of Orthopedics, Kunakorn Building, Fl.7, Faculty of Medicine, Thammasat University, Klong Luang 12120, Pathum Thani, Thailand

[2] Foot and Ankle Reconstruction/Arthroscopy and Athletic Injuries Knee and Ankle/Trauma, Department of Orthopaedics, St. Paul's Hospital, The University of British Columbia, Footbridge Clinic221-181 Keefer Place, Vancouver, BC V6B 6C1, Canada

spatiotemporal or gait parameters in patients with foot and ankle conditions during walking.

Materials and methods

Fifty-two patients with foot- and ankle-related conditions (37 female and 15 male, aged 21–75 years) were included in this study. Clinical assessments, including evaluation of validated patient-reported outcomes using the visual analog scale foot and ankle (VAS-FA) score [8], health-related quality of life using the validated Short Form-36 (SF-36) [9], and gait characteristics using a wearable foot inertial-sensor device, were performed and recorded for each patient. The exclusion criteria were as follows: age < 18 years, difficulty to bear weight on the involved foot without assistive device, significantly incomplete data, and cognitive dysfunction. Institutional review board approval was obtained, and informed consent was provided by all patients.

A foot pod (Garmin Ltd., Kansas City, USA) is a wearable device that uses micro-electromechanical systems (MEMS) inertial-sensor technology [10], which was used to assess the gait parameters in this study. The foot pod captured the following gait parameters: distance travelled, step count or length, cadence, and walking speed. Foot pod output could be wirelessly synced to a compatible smartphone or tablet. The data could also be shown in the computer via shared data from a compatible smartphone or tablet. Walking distance was set at 10 m with markings on the floor. For walking speed calibration of the foot pod, the task was performed on a treadmill at a controlled velocity of 0.28 m/s or 1 km/h over a 100-m distance.

For gait assessment, the foot pod was placed and strapped on the dorsum of the foot (1 fingerbreadth distal to the ankle area). The patients were instructed to walk a distance of 10 m for the walking trial at a self-selected speed. Their gait parameters were recorded and transferred to the computer.

Statistical analysis was performed using IBM SPSS software version 22 (SPSS Inc., Chicago, IL, USA). Differences in quantitative data were analyzed using Student's *t* test as the data were parametric. Differences in categorical data were analyzed using Chi-squared or Fisher's exact test. Pearson's correlation coefficient was used to express the correlation between the VAS-FA, SF-36 scores, and gait parameters. $P < 0.05$ was considered statistically significant.

Results

Mean age was 51.9 (± 13.7) years (range 21–75 years). Baseline data, including foot and ankle diagnoses and regions of pathology, are shown in Table 1. There were no significant baseline differences in age, VAS-FA, SF-36 scores, and gait parameters among all categories of foot and ankle conditions ($P > 0.05$, Table 1). Mean values of VAS-FA, SF-36 scores, and gait parameters are shown in Table 2.

Table 1 Baseline data

Foot and ankle pathology	Number (%)
Forefoot conditions	8 (15.4)
Injury	2 (3.8)
Deformity/arthritis	5 (9.6)
Infection	1 (1.9)
Midfoot conditions	2 (3.8)
Injury	1 (1.9)
Deformity/arthritis	1 (1.9)
Hindfoot conditions	21 (40.4)
Injury	5 (9.6)
Deformity/arthritis	9 (17.3)
Fasciitis/tendinopathy	7 (13.5)
Ankle conditions	16 (30.8)
Injury	7 (13.5)
Deformity/arthritis	9 (17.3)
Combined ankle-subtalar arthritis	2 (3.8)
Unspecified arthritis or diagnosis	3 (5.8)
Total	52 (100)

Table 2 Mean and standard deviation (SD) of visual analog scale foot and ankle (VAS-FA), Short Form-36 (SF-36), and kinematic gait parameters

Items[a]	Mean ± SD
VAS-FA	
Pain subscale	76.1 (32.6)
Function subscale	71.1 (24.4)
Other-related subscale	85.0 (15.7)
Total score	75.2 (22.9)
SF-36	
Physical component summary	64.4 (24.3)
Mental component summary	78.1 (22.2)
Total score	68.6 (22.2)
Mean speed (m/s)[b]	0.44 (0.22)
Maximum speed (m/s)	1.47 (0.15)
Step length (m/step)	0.64 (0.26)
Mean cadence (round/min)	44.43 (23.23)
Maximum cadence (round/min)	107.66 (14.82)

[a]The parameters were recorded from 52 patients with 53 measurements. (Two measurements were taken in a patient no. 11 with two different time points in around 7-week interval.) The health transition item in SF-36 was not included to calculate in a patient no. 11 at a second measurement due to the same value of both times of measurement

[b]Mean speed was detected by a foot pod in 46 patients. Other parameters were detected in all 52 patients

The correlations between age, VAS-FA, SF-36 scores, and gait parameters are shown in Tables 3 and 4. Only the negative correlation between physical component summary (PCS) and maximal cadence was significant ($r=-0.308$, $P=0.025$). In addition, the correlation between VAS-FA and SF-36 scores was high ($r=0.858$, $P<0.001$). Subgroup analysis was performed to assess whether heterogeneity in the assessed foot and ankle pathology was confounding the result between objective cadence and subjective patient-reported outcomes. As such, subgroup analysis was completed assessing the most common regions of foot and ankle pathology including combined ankle-subtalar arthritis pathology (2 patients) and isolated ankle arthritis (8 patients) (10 patients, 19.2%) and flatfoot (8 patients, 15.1%). In the group of combined ankle-subtalar arthritis pathology and isolated ankle arthritis, maximal cadences were significantly negatively correlated with VAS-FA ($r=-0.853$, $P=0.001$) and SF-36 scores ($r=-0.789$, $P=0.004$). The maximal cadences were also significantly negatively correlated with PCS ($r=-0.828$, $P=0.002$) and MCS ($r=-0.749$, $P=0.008$). In the flatfoot group, there were no significant correlations between gait parameters and VAS-FA or between gait parameters and SF-36 scores.

The inter-metric correlations between gait parameters were also analyzed in this study. Positive correlations between mean walking speed and mean cadence ($r=0.776$, $P<0.001$) and between maximal walking speed and mean step length ($r=0.498$, $P<0.001$) were observed. Negative correlations between mean cadence and mean step length ($r=-0.491$, $P<0.001$) and between maximal cadence and mean step length ($r=-0.355$, $P=0.009$) were noted. Subgroup analysis was also performed in the most common pathologies including combined ankle-subtalar arthritis pathology and isolated ankle arthritis and flatfoot. In the group of ankle with and without subtalar arthritis, maximal and mean cadences were significantly negatively and positively correlated with mean step length ($r=-0.704$, $P=0.016$) and mean walking speed ($r=0.774$, $P=0.005$), respectively. In the flatfoot group, mean cadence and mean step length were significantly positively correlated with mean walking speed as $r=0.803$, $P=0.030$ and $r=0.856$, $P=0.014$, respectively. The maximal cadence was significantly positively correlated with maximal walking speed ($r=0.716$, $P=0.046$).

Discussion

This study highlights the relationship between validated patient-reported outcome [8], health-related quality of life [9], and gait characteristics, which was assessed using a wearable foot inertial-sensor device in patients with foot and ankle conditions. The results show that cadence is a good

Table 3 Correlations between age, visual analog scale—foot and ankle (VAS-FA), and gait parameters

Items[a]	Age	VAS-FA							
		Pain subscale		Function subscale		Other-related subscale		Total score	
Mean speed[b] (m/s)	$R=-0.118$	$P=0.428$	$R=0.015$	$P=0.921$	$R=0.109$	$P=0.467$	$R=0.207$	$P=0.162$	$R=0.100$	$P=0.502$
Maximum speed (m/s)	$R=-0.034$	$P=0.811$	$R=0.079$	$P=0.572$	$R=0.089$	$P=0.525$	$R=0.176$	$P=0.208$	$R=0.104$	$P=0.460$
Step length (m/step)	$R=0.105$	$P=0.454$	$R=0.146$	$P=0.298$	$R=0.228$	$P=0.101$	$R=0.262$	$P=0.058$	$R=0.223$	$P=0.109$
Mean cadence (round/min)	$R=-0.128$	$P=0.359$	$R=-0.160$	$P=0.252$	$R=-0.071$	$P=0.614$	$R=-0.008$	$P=0.957$	$R=-0.093$	$P=0.508$
Maximum cadence (round/min)	$R=-0.060$	$P=0.669$	$R=-0.127$	$P=0.367$	$R=-0.195$	$P=0.162$	$R=-0.128$	$P=0.359$	$R=-0.208$	$P=0.135$

R, Pearson's correlation coefficients *r*; *P*, *P* value

[a]The parameters were recorded from 52 patients with 53 measurements. (Two measurements were taken in a patient no. 11 with two different time points in around 7-week interval)

[b]Mean speed was detected by a foot pod in 46 patients. Other parameters were detected in all 52 patients

Table 4 Correlations between Short Form-36 (SF-36) scores and gait parameters

Items[a]	SF-36		
	Physical component summary	Mental component summary	Total score
Mean speed[b] (m/s)	$R=0.164$	$R=0.195$	$R=0.211$
	$P=0.269$	$P=0.189$	$P=0.154$
Maximum speed (m/s)	$R=0.050$	$R=0.198$	$R=0.106$
	$P=0.724$	$P=0.156$	$P=0.451$
Step length (m/step)	$R=0.219$	$R=0.185$	$R=0.232$
	$P=0.115$	$P=0.184$	$P=0.095$
Mean cadence (round/min)	$R=-0.027$	$R=-0.031$	$R=-0.015$
	$P=0.849$	$P=0.824$	$P=0.913$
Maximum cadence (round/min)	$R=-0.308$*	$R=-0.238$	$R=-0.264$
	$P=0.025$	$P=0.086$	$P=0.056$

R, Pearson's correlation coefficients *r*; *P*, *P* value

*Significant value at $P<0.05$

[a]The parameters were recorded from 52 patients with 53 measurements. (Two measurements were taken in a patient no. 11 with two different time points in around 7-week interval.) The health transition item in SF-36 was not included to calculate in a patient no. 11 at a second measurement due to the same value of both times of measurement

[b]Mean speed was detected by a foot pod in 46 patients. Other parameters were detected in all 52 patients

objective predictor of foot and ankle function and is related well to subjective patient-reported outcomes as there is a significant negative relationship between PCS and maximal cadence. In the subgroup analysis of patients who had combined ankle-subtalar arthritis pathology and isolated ankle arthritis, maximal cadence was also significantly negatively correlated with subjective patient-reported outcomes. No significant correlations between other items of outcome score or health-related quality of life and parameters of gait characteristics were found [9].

Moreover, increased cadence was significantly related to a decreased PCS value in health-related quality of life [9]. Patients who were in poor physical condition due to foot and ankle conditions demonstrated compensatory gait mechanisms resulting in an increased cadence to maintain their walking speed. This finding was consistent with the evidence presented by Schmitt et al., who found that the presence of end-stage osteoarthritis at various lower extremity joints results in compensatory gait mechanisms that cause movement alterations throughout the lower extremity [11]. Cadence was also significantly positively correlated with walking intensity; patients with increased cadence need more energy during walking [12]. This may be a vicious cycle in these patients with poor physical condition. Furthermore, cadence shows a significant relationship with physical outcome in this study and walking intensity in a previous study. Therefore, cadence is an essential parameter in gait studies to objectively assess outcome of patients with foot and ankle pathology and can be used effectively in epidemiological studies, interventions and behavioral research, dose–response studies, determinant studies, and practice [12].

For the inter-metric relationship, significantly positive correlations between mean walking speed and mean cadence and between maximal walking speed and mean step length were observed. Significantly negative correlations between mean cadence and mean step length and between maximal cadence and mean step length were also noted. The results of subgroup analysis were quite similar to the results in the overall analyses, indicating that these pathologies were not confounding the relationship between cadence and self-reported outcomes. This evidence supports the compensatory gait mechanisms that resulted in significant relationships between several parameters. Moreover, Aguilar-Ferrándiz et al. [13] showed that stance phase and step length do not improve in patients with ongoing conditions of the lower limb. The symptomatic patients in the present study possibly had reduced stance phase because of their painful symptoms [14], impaired range of motion or strength, deformities, or imbalances due to their foot and ankle conditions. In accordance with Cadenas-Sanchez et al. [15], a reduced support phase as part of the stance phase during walking showed a similar trend with reduced step length, which significantly correlated with decreased walking speed in the present study. These changes were compensated by increased cadence to maintain the patients' walking speed, i.e., walking speed = step length × cadence [16]. A significant relationship was also found between increased cadence and decreased step length as a compensatory mechanism. Hence, cadence is a key parameter for compensatory gait

mechanisms in patients with foot and ankle conditions. This spatiotemporal parameter is easily interpretable by researchers and clinicians and therefore offers the potential to link science, practice, and real life [12].

The limitations of this study include the heterogeneity of foot and ankle conditions in the study subjects. Nevertheless, there were no significant differences for age, VAS-FA, SF-36 scores, and gait parameters among the varied regions of foot and ankle conditions included. Subgroup analysis was also performed to assess whether subgroups of pathology may be confounding the results, such as combined ankle-subtalar arthritis pathology and isolated ankle arthritis and flatfoot. Subgroup analysis did not result in varying findings, indicating that these subgroups were not confounding the relationships observed between cadence and subjective patient-reported outcomes, and supported the results from the overall analysis. In addition, this study is quite unique in that it determined the relationship between subjective validated patient-reported outcome [8], health-related quality of life [9], and objective gait characteristics using a wearable foot inertial-sensor device in patients with foot and ankle pathology.

Conclusions

Regarding the relationships among several spatiotemporal parameters and patient-reported outcome measures, cadence is the only objective parameter that is significantly negatively related to subjective parameter PCS in health-related quality of life. Thus, cadence is an essential parameter for compensatory gait mechanisms in patients with foot and ankle conditions and should be assessed in clinical practice.

Compliance with ethical standards

Conflict of interest The first author reports personal fees from Amgen, Device Innovation, Phoenix surgical equipment (Thailand), Novatec Healthcare (Thailand), Pfizer, Eisai (Thailand), Symgens, Smith & Nephew, and Bangkok Unitrade outside the submitted work. The second author reports grants from Acumed, grants from Zimmer, grants from Bioventus, from null, grants from Wright medical, grants from Arthrex, grants from Synthes, grants from Ferring, and grants from Amniox, outside the submitted work.

References

1. Angthong C (2016) Validity and reliability of Thai version of the foot and ankle outcome score in patients with arthritis of the foot and ankle. Foot Ankle Surg 22:224–228
2. SooHoo NF, Shuler M, Fleming LL, American Orthopaedic Foot and Ankle Society (2003) Evaluation of the validity of the AOFAS clinical rating systems by correlation to the SF-36. Foot Ankle Int 24:50–55
3. Richter M, Zech S, Geerling J, Frink M, Knobloch K, Krettek C (2006) A new foot and ankle outcome score: questionnaire based, subjective, visual-analogue-scale, validated and computerized. Foot Ankle Surg 12:191–199
4. American Orthopaedic Foot and Ankle Society (AOFAS) (ed) (2003) Symposium X—outcomes assessment in foot and ankle surgery—What instrument should we use?
5. Rosenlund S, Holsgaard-Larsen A, Overgaard S, Jensen C (2016) The gait deviation index is associated with hip muscle strength and patient-reported outcome in patients with severe hip osteoarthritis: a cross-sectional study. PLoS ONE 11:e0153177
6. Van der Linden ML, Hooper JE, Cowan P, Weller BB, Mercer TH (2014) Habitual functional electrical stimulation therapy improves gait kinematics and walking performance, but not patient-reported functional outcomes, of people with multiple sclerosis who present with foot-drop. PLoS ONE 9:e103368
7. Van Hoeve S, de Vos J, Verbruggen JP, Willems P, Meijer K, Poeze M (2015) Gait analysis and functional outcome after calcaneal fracture. J Bone Joint Surg Am 97:1879–1888
8. Angthong C, Chernchujit B, Suntharapa T, Harnroongroj T (2011) Visual analogue scale foot and ankle: validity and reliability of Thai version of the new outcome score in subjective form. J Med Assoc Thai 94:952–957
9. Jirarattanaphochai K, Jung S, Sumananont C, Saengnipanthkul S (2005) Reliability of the medical outcomes study short-form survey version 2.0 (Thai version) for the evaluation of low back pain patients. J Med Assoc Thai 88:1355–1361
10. Maenaka K (2008) MEMS inertial sensors and their applications. In: 2008 5th International conference on networked sensing systems, Kanazawa, pp 71–73. http://dx.doi.org/10.1109/INSS.2008.4610859
11. Schmitt D, Vap A, Queen RM (2015) Effect of end-stage hip, knee, and ankle osteoarthritis on walking mechanics. Gait Posture 42:373–379
12. Tudor-Locke C, Rowe DA (2012) Using cadence to study free-living ambulatory behaviour. Sports Med 42:381–398
13. Aguilar-Ferrándiz ME, Moreno-Lorenzo C, Matarán-Peñarrocha GA, García-Muro F, García-Ríos MC, Castro-Sánchez AM (2014) Effect of a mixed kinesio taping-compression technique on quality of life and clinical and gait parameters in postmenopausal women with chronic venous insufficiency: double-blinded, randomized controlled trial. Arch Phys Med Rehabil 95:1229–1239
14. Schroeder JB (2009) Case 2: a gait to remember. Paediatr Child Health 14:189–192
15. Cadenas-Sanchez C, Arellano R, Vanrenterghem J, López-Contreras G (2015) Kinematic adaptations of forward and backward walking on land and in water. J Hum Kinet 49:15–24
16. Bayle N, Patel AS, Crisan D, Guo LJ, Hutin E, Weisz DJ, Moore ST, Gracies JM (2016) Contribution of step length to increase walking and turning speed as a marker of Parkinson's disease progression. PLoS ONE 11:e0152469