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Instrumented joint mobility analysis in traumatic transtibial amputee patients

IDA KOVAČ[1]
VLADIMIR MEDVED[2]
MARIO KASOVIĆ[2]
ŽELJKO HEIMER[3]
VESNA LUŽAR-STIFFLER[4]
MARKO PEĆINA[5]

[1] Institute for Rehabilitation and Orthopedic Devices
University Hospital Center Zagreb
Božidarevićeva 11
10 000 Zagreb, Croatia

[2] Faculty of Kinesiology
University of Zagreb
Horvaćanski zavoj 15
10000 Zagreb, Croatia

[3] Ministry of Defence of the Republic of Croatia,
Trg Kralja Petra Krešimira IV
10 000 Zagreb, Croatia

[4] CAIR Research Center and
University of Zagreb
Josipa Marohnića 5
10000 Zagreb, Croatia

[5] Medical school
University of Zagreb
Šalata 3
10000 Zagreb, Croatia

Correspondence:
Ida Kovač
Institute for Rehabilitation and Orthopedic Devices
University Hospital Zagreb
Božidarevićeva 11
10 000 Zagreb, Croatia
E-mail: idakovac@mail.inet.hr

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Abstract

Aim: *The presented study reports a quantitative gait analysis and different adaptive strategies evaluation on 12 male adults, war trauma transtibial (TT) amputees, fitted with prostheses.*

Methods*: Gait analysis included kinematics (joint mobility variables) prosthetic and healthy legs in 12 TT amputees and 12 able-bodied persons/individuals.*

Results*: The results disclose asymmetry in gait parameters between the amputated and sound legs, as well as between transtibial amputees and able-bodied persons. Kinematic results of the amputees and a control group, showed significantly reduced prosthetic maximum ankle plantar flexion ($p<0.01$), decreased hip adduction ($p< 0.05$) and increased knee flexion at stance phase ($p< 0.1$) for the left, healthy legs of amputees.*

Conclusion*: Although adult traumatic TT amputees have great potential for enhancement of function through appropriate rehabilitation and use of effective prosthetic devices, they adapt a unique way of ambulating with the prosthesis. An instrumented gait analysis study is able to provide assessment of the way prosthetic transtibial amputees walk, as objective information to supplement clinical observation.*

INTRODUCTION

During the war in Croatia (1991–1995) in the Institute for Rehabilitation and Orthopedic Devices, 864 amputated casualties were rehabilitated and prosthetically equipped *(1)*. Amputees with war trauma related amputation represent a very specific group of patients, first of all because of their age (working age adults). It is well known that amputation has significant impact on employment and the quality of life during the next 40 to 50 years of the remaining life of these young people. They have great potential for enhancement of function through appropriate rehabilitation and use of effective prosthetic devices. Very often they adapt a unique way of ambulating with the prosthesis, and consequently the biomechanical profile of walking differs from that of able-bodied persons. Most of the adaptations in their walk can be discerned by observation, although it is not sufficient to merely note walking complexity, and therefore objective gait analysis becomes necessary.

Kinematic, kinetic and electromyography parameters are very important for evaluation of the biomechanical profile of a person's gait because they provide basic quantitative information for the study of specific phases in the gait cycle. Kinematic, temporal-spatial and joint mobility parameters, characterize the motion of the body and limb segments through space during representative walking strides. The most commonly used temporal-spatial parameters are: walking velocity, step length, stride length and cadence *(2–9)*. While healthy persons walk displaying almost symmetrical parameters for the right and left leg, amputee subjects, using a prosthesis, typically demonstrate gait patterns that are different from those of able-bodied individuals. The more distal the amputation, the better control the amputee has of his prosthesis, the more efficient the gait, and the more closely their pattern of walking resembles that of able-bodied persons *(8, 10)*.

MATERIALS AND METHODS

Patient population

The study population consisted of twelve (12) males with right trans-tibial traumatic amputation, mean age 40.25+6 years (31–52), who volunteered to participate in this study.

They were all war victims, mostly injured by land mines, in/during the period 1991–1995. All patients had completed a prosthetic training program in the Institute for Rehabilitation and Orthopedic Devices (IROD) University Hospital Centre Zagreb. All subjects were excellent walkers who used their prosthesis on a regular basis and were leading an active normal life. They were not suffering from any severe concurrent illnesses (Table 1).

Prosthetic alignment was similar for all patients. All transtibial prostheses had full contact socket with prosthetic feet; they were similar, but not the same type (Dynamic foot: 7 patients, Greissenger foot: 2 patients and Flex foot walk: 2 patients). The sample for the study was selected to be homogeneous according to etiology of amputation, gender and age of amputees, but it was not possible to provide the same type of all prosthetic components. The time lapse between the date of amputation and the time of testing ranged from 8 to 12 years (mean time lapse10.08+1.5 years). The control group consisted of 12 male non-amputees with normal gait, mean age 37.46 ± 5.25 years (27–44). The control group subjects were members of the Croatian Armed Forces, who volunteered to participate in the study, and who were not specially trained in any sport or other physical activity. Their anthropometric characteristics were similar to those of the amputees.

TABLE 1

Study population: 12 males with right transtibial traumatic amputation and a control group of 12 able-bodied males, without amputation.

	Study population: 12 males with right TT traumatic amputation	Control group: 12 males without amputation
Mean age (yrs)	40.25 ± 6 (31–52)	37.46 ± 5.25 (27–44)
Body mass (kg)	88.08 ± 16.5 (62–111)	86.38 ± 10.03 (74–103)
Height (cm)	182.08 ± 5.1 (175–191)	177.9 ± 5.0 (173–188)

METHODS

Instrumented gait analysis was performed by simultaneously measuring kinematic, kinetic and dynamic electromyography (EMG) data. Gait analysis consists of both amputated and non-amputated legs data, compared to data for able-bodied persons. Kinematics measurements were provided by optoelectronic system Elite Biomech (BTS Bioengineering, Milan) with eight cameras (100 Hz, high-speed video system (2 camera 30 Hz) and control PC unit, including adequate software *(11)*. Markers were placed over predefined body landmarks on the trunk, pelvis and legs, examining 3 joints each, in 2 limbs, in the saggital, frontal and transverse plane, according to Davis protocol *(12)*. As the patient walks through the lab (laboratory), multiple infrared cameras detect the three-dimensional location of each marker. They were used to track the 3-dimensional locations of individual body segments throughout the gait cycle. A biomechanical model was applied to the marker series to calculate the three-dimensional motion of each body segment. Kinematic measurements (temporal and distance parameters) and measurements of joint motions of hips, knees and ankles, which provide fundamental timing and position information about a person's gait, were analyzed. Kinetic analyses were performed by collection of ground reaction

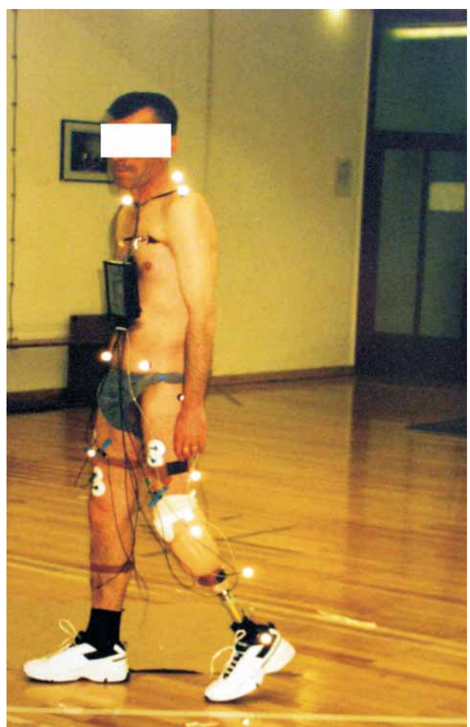

Figure 1. *Patient equipped with reflective markers walking through the motion analysis center.*

force data as the subjects walk over a force plate (Kistler) embedded into the floor of the laboratory (12 m long walkway) (instrumented with force plate (Kistler)). After a period of adaptation to the laboratory conditions and the equipment used and after information about the purpose of the study, the subject was asked to walk at free cadence (Figure 1) *(11, 13)*. The experimental sessions were carried out in the Biomechanic Laboratory at the Faculty of Kinesiology in Zagreb. Prosthetic rehabilitation of all TT amputees was performed in the Institute for Rehabilitation and Orthopedic Devices University Hospital Center Zagreb. (After a period of adaptation to the laboratory conditions and the equipment used and after informing about the purpose of study, the subject was asked to walk at free cadence (Figure 1).

Statistical analysis

Of all the variables studied, a total of 11 kinematic variables: 6 temporal parameters and 5 distance parameters, 13 variables of joint motions of hips, knees and ankles and 7 kinetic variables (ground reaction forces) of gait cycle were selected and studied for the group of 12 TT amputees and for 12 non-amputees. The kinematic and kinetic data were processed by using means differ-

TABLE 2

Results of kinematic measurements (means and standard deviations) of range of joint motions (hips, knees and ankles) for amputees and able-bodied persons.

Variable	Leg	No of measurements	Mean values	Standard deviation
H1	R PRO A	13	36.66	10.78
H1	R L C	13	37.80	7.85
H1	L L A	13	37.87	9.23
H1	L L C	13	37.43	7.04
H2	R PRO A	13	–4.42	9.00
H2	R L C	13	–6.73	4.73
H2	L LA	13	–3.04	8.57
H2	L L C	13	–8.78	4.90
H3	R PRO A	12	5.17	12.29
H3	R L C	13	–1.48	4.15
H3	L LA	12	6.05	8.63
H3	L L C	13	–1.55	4,00
H4	R PRO A	13	37.92	6.35
H4	R L C	13	37.92	6.35
H4	L L A	13	39.22	8.82
H4	L L C	13	36.69	6.31
H5	R PRO A	13	4.66	4.26
H5	R L C	13	5.01	2.98
H5	L L A	13	7.32	3.27
H5	L LC	13	3.93	3.42
H6	R PRO A	13	–7.55	3.88
H6	R L C	13	–9.19	4.05
H6	L L A	13	–3.98	4.34
H6	L L C	13	–10.08	4.15
K1	R PRO A	12	8.98	10.43
K1	R L C	13	8.54	4.23
K1	L L A	12	4.51	5.17
K1	L L C	13	8.69	5.11
K2	R PRO A	12	18.13	10.14
K2	R L C	13	24.69	6.62
K2	L L C	12	24.53	9.30
K2	L L A	13	22.28	5.39
K3	R PRO A	12	8,00	10.11
K3	R L C	13	6.48	1.78
K3	L L A	12	6.92	7.75
K3	L L C	13	5.66	2.78
K4	R PRO A	12	71.37	12.40
K4	R L C	13	64.23	7.60
K4	L LA	12	66.04	9.14
K4	L L C	13	65.31	5.32
K5	R PRO A	12	39.832 9	5.89
K5	R L C	13	38.436 7	4.09
K5	L LA	12	45.435 8	9.70
K5	L L C	13	37.77	3.86
A1	R PRO A	12	11.90	4.95
A1	R L C	13	12.31	2.39
A1	L L A	12	13.56	4.06
A1	L L C	13	14.54	4.38
A2	R PRO A	12	2.10	3.31
A2	R L C	13	–13.20	5.27
A2	L L A	12	–12.04	5.10
A2	L L C	13	–11.27	6,00

Legend: H1 – hip flexion on heel strike, H2 – hip flexion on peak stance extension, H3 – hip flexion on toe-off, H4 – hip flexion on peak swing flexion, H5 – hip max. abduction, H6 – hip max. adduction; K1 – knee flexion on heel strike, K2 – knee flexion on loading response, K3 – knee flexion before toe off, K4 – max. knee flexion on peak swing flexion and K5 – knee flexion at the end of stance phase, on toe off; A1 – ankle dorsiflexion on loading response in stance phase and A2 – max. ankle plantar flexion at the end of stance phase, on toe off.

R PRO A – right leg (prosthesis) of amputees; L L A – left leg (sound) of amputees; R L C – right leg of able-bodied persons of control group; L L C – left leg of able-bodied persons of control group

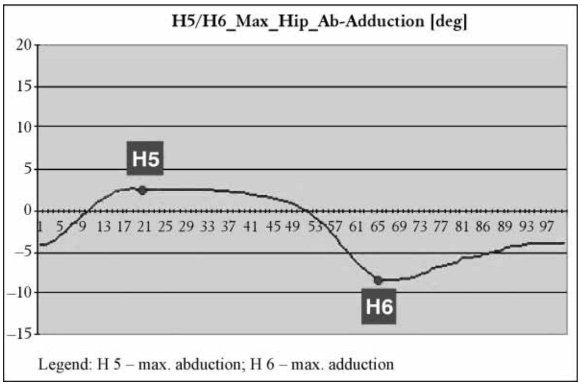

Figure 2a. *Graphic presentation of kinematic analysis of hip range of motion (abduction / adduction) with the marks (H5, H6) during gait cycle, measurements were done.*

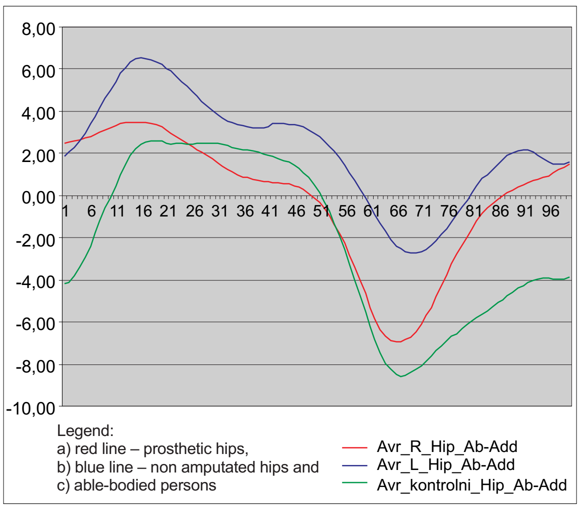

Figure 2b. *Graphic presentation of kinematic results of hip range of motion (abduction/ adduction) during gait cycle for amputees and able-bodied persons.*

ences with standard t-test; p-tests were modified because of multiple tests (3x12= 36; 3x13= 39 and 4x7=28). Statistical MULTTEST Statistical Software SAS procedure was used. Kinematic results were compared, by means of a statistical method in several ways: a) in general: TT amputees – able bodied persons, b) right, prosthetic legs of TT amputees – right legs of non-able bodied persons and c) left legs of TT amputees – left legs of non able bodied persons. Further measurement results of prosthetic legs were analyzed by comparison with the results of left, healthy legs of amputees.

RESULTS

Results of the range angles of joint motion measurements, presented by means and standard deviations (Table 2) and by means of graphical presentation for range angle motion for hips (Figure 2 b), knees (Figure 3 b) and ankles (Figure 4 b) of amputees (prosthetic legs and

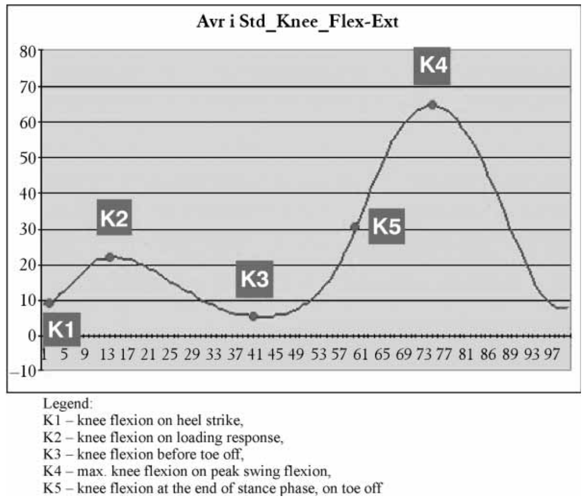

Figure 3a. *Graphic presentation of kinematic analysis of knee range of motion with the marks (K1, K2, K3, K4, K5) during gait cycle (measurements were done).*

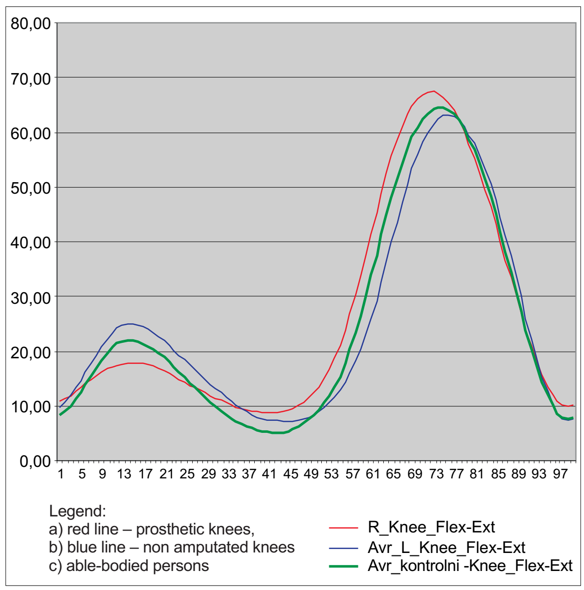

Figure 3b. *Graphic presentation of kinematic results of knee range of motion (Knee Flex-Extension) during gait cycle for amputees and able-bodied persons.*

healthy legs) and both legs of able bodied persons during the gait cycle were determined. Range of hip flexion/ extension were measured at flexion on heel strike (H1), on peak stance extension (H2), on toe-off (H3), on peak swing flexion (H4) and hip range of motion (abduction/ adduction) with max. abduction (H5) and max. adduction (H6) (Figure 2 a). For knee joints, several angle motions were measured such as knee flexion on heel strike (K1), knee flexion on loading response (K2), knee flexion before toe off (K3), max. knee flexion on peak swing flexion (K4) and knee flexion at the end of the stance phase, on toe off (K5) (Figure 3 a). Ankle joint angle was

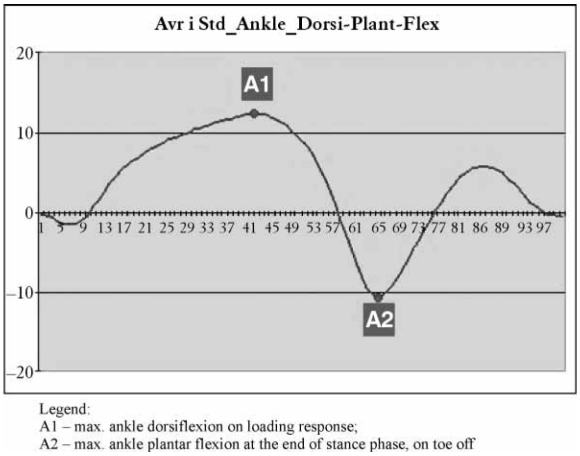

Figure 4a. *Graphic presentation of kinematic analysis of ankle range of motion with the marks A1, A2) during gait cycle (were measurements were done?).*

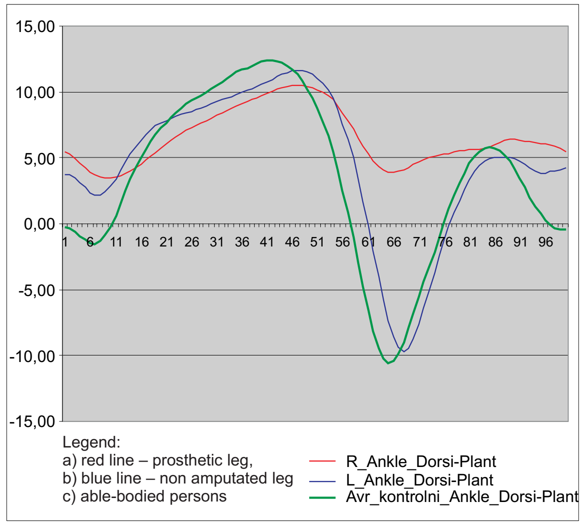

Figure 4b. *Graphic presentation of kinematic results of ankle range of motion for amputees and able-bodied persons during gait cycle.*

measured by max. ankle dorsiflexion on loading response in stance phase (A1) and max. ankle plantar flexion at the end of stance phase, on toe off (A2) (Figure 4 a).

Comparison of the results of joint movement analysis, presented in Table 3, between amputee persons and a control group of persons without amputation, (AP-CG: amputees-control group), in general showed statistically significant differences for several parameters: 1) hip range of motion, max. adduction (H6); $p = 0.0350$ ($p< 0.05$), 2) hip range of flexion/ extension at toe-off (H3); $p = 0.0662$ ($p<0.1$) and 3) max. ankle plantar flexion at the end of the stance phase, on toe off (A2); $p= 0.001$ ($p<0.01$). Comparison of joint movement results between prostheses, right legs of amputee persons and right legs of able-bodied persons of the control group, showed statistically significantly decreased max. ankle plantar flexion at the end of the stance phase, on toe off (A2) for prosthetic legs (2.10 ± 3.31 vs. 13.20 ± 5.27), $p = 0.0001$ ($p<0.01$). Comparison of joint movement analysis, between the amputees and the control group, and the left legs of amputee persons with the left legs of able-bodied persons, showed statistical significance for two parameters: 1) decreased hip range of motion – max. adduction (H6); 3.80±4.34° vs.10.08 ± 4.15, $p= 0.0109$ ($p< 0.05$) and 2) increased knee flexion at the end of stance phase, on toe off (K5); 45.4358 ± 9.70 vs. 37.77 ± 3.86, $p= 0.0899$ for left, healthy legs of TT amputees.

Maximal range of joint motion measurements for hips (flexion/extension and abduction/adduction), knees (flexion/extension) and ankles (dorsiflexion/plantar flexion) were examined and the results compared between amputees and able-bodied, right prosthetic legs to left, sound legs of amputees and left legs of amputees to left legs of able-bodied persons. The most remarkable results of mea-

TABLE 3

Results of standard and modified t-tests (p-values) of kinetic parameters (GRF) comparing: a) amputees to able-bodied persons, b) right prosthetic legs to left, sound legs of amputees and c) left legs of amputees to left legs of able-bodied persons.

p-values			
Variables	Comparison	Standard t-test	Modified t-test
A2 – max. ankle plantar flexion at the end of stance phase, on toe off	CG vs. AP	<.0001	0.0001***
A2 – max. ankle plantar flexion at the end of stance phase, on toe off	R L C vs.R PRO A	<.0001	<.0001***
H6 – max. hip adduction	CG vs. AP	0.0014	0.0350**
H6 – max. hip adduction	L L C vs. L L A	0.0004	0.0109**
H3 – hip flexion on toe-off	CG vs. AP	0.0026	0.0662*
K5 – knee flexion at the end of stance phase, on toe off	L L C vs. L L A	0.0036	0.0899*

Legend: H3 – hip flexion on toe-off, H6 – hip max. adduction; K5 – knee flexion at the end of stance phase, on toe off; A2 – max. ankle plantar flexion at the end of stance phase, on toe off

R PRO A – right leg (prosthesis) of amputees; L L A – left leg (sound) of amputees; R L C – right leg of able-bodied persons, control group; L L C – left leg of able- bodied persons, control group; AP-CG: amputees-control group

/* 0. 05< p< 0. 1 /** 0. 01<p<0. 05 /*** p<0. 01)

TABLE 4

Results of kinematic measurements (means and standard deviations) of ankle maximal dorsiflexion/ plantar flexion for amputees and able-bodied persons.

Variables	Group	Number of persons	Mean values	Standard deviations
ankle flexion-extension	R PRO A	12	15.16	6.51
ankle flexion-extension	R L C	13	25.51	4.45
ankle flexion-extension	L L A	12	25.60	4.06
ankle flexion-extension	L L C	13	25.81	4.07

Legend: R PRO A – right leg (prosthesis) of amputees; L L A – left leg (sound) of amputees; R L C – right leg of able-bodied persons of control group; L L C – left leg of able-bodied persons of control group

surements (means and standard deviations) of ankle maximal dorsiflexion/ plantar flexion are presented in Table 4 and Table 5. Among all variables for maximal range of motions for hip, knees and ankles, statistically significant differences were obtained for ankle movement (dorsiflexion/ plantar flexion), comparing amputees to able-bodied persons (p=0. 0034 ***) and right prosthetic legs to right legs of able-bodied persons p= 0.0001*** (15,16± 6,51 vs. 25,51 ± 4,45), p = 0.0001 (p<0.01) (Table 4 and Table 5).

TABLE 5

Statistical significant results of standard and modified t-tests (p-values) for maximal ankle mobility (dorsiflexion/ plantar flexion) comparing: a) amputees to able-bodied persons, b) right prosthetic legs to left, sound legs of amputees and c) left legs of amputees to left legs of able-bodied persons.

p-values Variables	Comparison	Standard t-test	Modified t-test
ankle flexion/ extension	CG vs. AP	0.0004	0.0034*** p<0,01
ankle flexion/ extension	R L C vs. R PRO A	<.0001	0.0001*** p<0,01

Legend: R PRO A – right leg (prosthesis) of amputees; L L A – left leg (sound) of amputees; R L C – right leg of able-bodied persons, control group; L L C – left leg of able-bodied persons, control group; AP – CG: amputees – control group

/* 0, 05< p< 0, 1 /** 0, 01<p<0, 05 /*** p<0, 01)

DISCUSSION

The results of our gait analysis disclose asymmetry in kinematic gait parameters between the amputated and sound legs, as well as between trans-tibial amputees and non-disabled persons, which was confirmed by the statistical tests. Comparison of the results of our study with amputee gait studies by other authors was rather difficult because of the great variability of gait studies according to etiology or age of the study population. Our patients were young adults while most studies comprised older amputees or children. The problem was also the lack of similar studies on traumatic amputees. Other problems were the variety and great number of different measurement methodologies and equipment used in biomechanical analysis. Consequently, our results were difficult to compare with those of other studies.

The results of joint mobility measurements showed that trans-tibial amputees tend to walk with similar kinematics as able-bodied individuals, although subtle differences could be distinguished. Amputation is not the only reason for biomechanical changes on the remaining joint of the amputated leg but it is also the reason for compensatory kinematic changes on the joints of the sound leg *(14)*. Increased joint mobility of the knee, on the prosthetic leg at the moment of heel strike, compared to the other, healthy leg, observed in our study, was also reported by Isakov, Burger and coauth. *(15)*, Bateni and Olney *(16)* and Isakov and coauthors *(9)*. The greatest hip mobility (flexion/ extension) on heel strike on the amputated leg, compared to the healthy leg and able bodied persons measured in our study was also observed by Isakov and coauthors *(15)*.

On the other hand, some other authors such as Winter and Sienko *(17),* Colborne and coauthors *(18)* and Bateni and Olney *(16)* reported reduced hip mobility range. They also reported increased knee mobility (knee flexion) during the swing phase, compared to the healthy leg of amputees, which we also observed *(16, 17, 18)*. The most remarkable difference, which reached statistical significance, was reduced ankle joint mobility on the prosthesis, compared to healthy legs of amputees (15.16 ±6,51 vs. 25.60 ± 4,06) and able bodied persons (25.51±4,45). Primarily, the ankle kinematics of their prosthetic limb differs from the normal pattern due to the inability to plantar flex in the late stance phase. Increased hip flexion angles during early stance phase could be speculated to be a compensatory action to prolong the prosthetic stride or the result of small (slight) anteflexion of the body. Amputees have reduced stability on the prosthetic leg and to improve it, the body anteflexion is a compensatory reaction to transfer gravity center forward. According to Whitle *(6)* kinematic analysis of amputees shows the individual's gait performance, some of which showed almost normal gait. From the kinematic point of view, the main cause of gait differences of amputees is the type of prosthetic foot, because of the tehnical characteristics of the prosthetic ankle. The ability of dorsiflexion and plantar flexion of the foot, although it is reduced, gives the posibility of dorsiflexion during middle to late stance phase and increases pressure of the forefoot. Reduced plantar flexion is a result of increased push off ability of the prosthetic foot at the late stance phase. The prosthetic feet of our patients were the dynamic type (and not the SACH type), and thus this analysis is acceptable for our kinematic results.

CONCLUSION

Patients with traumatic amputations adapt a unique way of ambulating with the prosthesis. Most adaptations can be discerned by means of observation although it is not sufficient to note walking complexity. The goal of gait analysis is the comparison of normal gait pattern with abnormal patterns, and another more difficult part in the task of understanding the mechanisms of the gait disorders of amputees is discrimination of primary mechanisms of abnormal performance from the compensatory mechanisms. The study results of our gait analysis of traumatic amputees, who had been walking with a prosthesis for more than 8 years, discloses asymmetry in kinematic gait parameters between the amputated and contra lateral, left sound legs of amputees, as well as between prosthetic, right legs of transtibial amputees and both legs of non-disabled persons (particularly with right legs). Biomechanical, kinematic and kinetic, measurements of walking are useful because they provide objective assessment of the way prosthetic persons walk. In order to better understand the complexity of the amputee gait, with discrimination of primary mechanisms of abnormal performance from the compensatory mechanisms, objective gait analyses should provide objective assessment on the way prosthetic persons walk and convey information that cannot be discerned visually by an observer. Better understanding of the biomechanics of the gait of trauma related amputees could be the basis for intervention strategies that enhance the prospect of maximal functional restoration and provide design guidance for prosthetic components in transtibial amputees *(2, 10, 19)*. The overall goal of amputee rehabilitation is to return patients to their highest level of function and safety. Instrumented, computerized 3-D gait analysis can be one tool to facilitate this *(20, 21)*.

REFERENCES

1. JELIĆ M, KOVAČ I 2002 Epidemiological analysis of war amputees. *In:* Book of abstracts Third ISPO Central and Eastern European Conference. Dubrovnik; October 23–25, p 61
2. ESQUENAZI A, KEENAN M A 2007 Gait analysis. *In:* Braddom R.L. Physical medicine and Rehabilitation. Third Edition. *Saunders Elselvier:* 93–111
3. DILLINGHAN T R, PEZZIN L E, MACKENZIE E J 1998 Incidence, acute care length of stay, and discharge to rehabilitation of traumatic amputee patient: an epidemiologic study. *ArchPhys Med Rehabil 79:* 279–287
4. GARD S A 2006 Use of quantative gait analysis for the evaluation of prosthetic walking performance. *JPO 18:* 93–104
5. REITMAN J S, POSTEMA K, GEERTZEN J H B 2002 Gait analysis in prosthetics: opinions, ideas and conclusions. *Prosthet Orthot Int 26:* 50–57
6. WHITTLE M 2002 Gait Analysis: An Introduction. Third Edition. Oxford: Butterworth-Heinemann.
7. WU G 1995 Kinematics Theory. *In:* Craik R, Oatis C. Gait Analysis. Theory and Application. St. Luis. *Mosby:* 160–182
8. BRAKEY J 1976 Gait of unilateral bellow-knee amputees. *Orthot Prosthet 30:* 17–24
9. ISAKOV E, BURGER H, KRAJNIK D S, GREGORIĆ M, MARINČEK C 1997 Double-limb support and step-length asymmetry in below-knee amputees. *Scand J Rehab Med:* 75–79
10. WINTER D A 1991 Kinetics. *In:* The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological. Sec ed. Walerloo Ontario Canada. *Waterloo Press:* 35-41
11. BTS 2003 Declaration of ELITE system characteristics. BTS S.p.A., Milano.
12. DAVIS R, OUNPUU S, TYBURSKI D, GAGE J R 1991. A gait analysis data collection and reduction technique. Human Movement Science. *North Holland 10:* 575–587
13. MEDVED V 2001 Measurement of Human Locomotion. CRC Press LLC. New York, p 1–4
14. PERRY J, BOYD L A, RAO S S, MULROY S J 1997 Prosthetic weight acceptance mechanics in transtibial amputees wearing the Single axis, Seatlle Lite, and Flex Foot. *IEEE Trans Rehabil Eng 5:* 283–384
15. ISAKOV E, BURGER H, KRAJNIK D S, GREGORIĆ M, MARINČEK C 1996 Influence of speed on gait parameters and on symmetry in below-knee amputees. Proceedings of 9th International conference Mechanics in Medicine and Biology Ljubljana, June 1996. Ljubljana, p 453-456
16. BATENI H, OLNEY S 2002 Kinematic and Kinetic Variations of Below-Knee Amputee Gait. *J Prosthet Orthot Sci JPO 14(1):* 2–10
17. WINTER D A, SIENKO S E 1988 Biomechanics of below-knee amputee gait. *J Biomech 21:* 361–367
18. COLBORNE G R, NAUMANN S, LONGMUIR P E, BERBRAYER D 1992 Analysis of mechanical and metabolic factors in the gait of congenital below knee amputees: A comparison of the SACH and Seattle feet. *Am J Phys Med Rehabil 71:* 272–278
19. WINTER D A 1987 The Biomechanics and Motor Control of Human Gait. University of Waterloo Press.,Waterloo.
20. HEIMER Ž 2005 Automated clinical measurement of biomechanics and kinesiology of human gait. (MS thesis), (in Croatian), University of Zagreb, Zagreb.
21. KOVAC I 2007 Biomechanical gait analysis of transtibial amputees´ fitted with Patellar Tendon Bearing Prosthesis. (PhD thesis), (in Croatian) University of Zagreb, Zagreb.