

Factors that predict walking ability with a prosthesis in lower limb amputees

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SUMMARY

Introduction Identification of predictive factors for walking ability with a prosthesis, after lower limb amputation, is very important in order to define patient's potentials and realistic rehabilitation goals, however challenging they are.

Objective The objective of this study was to investigate whether variables determined at the beginning of rehabilitation process are able to predict walking ability at the end of the treatment using support vector machines (SVMs).

Methods This research was designed as a retrospective clinical case series. The outcome was defined as three-leveled ambulation ability. SVMs were used for predicting model forming.

Results The study included 263 patients, average age 60.82 ± 9.27 years. In creating SVM models, eleven variables were included: age, gender, cause of amputation, amputation level, period from amputation to prosthetic rehabilitation, Functional Comorbidity Index (FCI), presence of diabetes, presence of a partner, restriction concerning hip or knee extension, residual limb hip extensor strength, and mobility at admission. Six SVM models were created with four, five, six, eight, 10, and 11 variables, respectively. Genetic algorithm was used as an optimization procedure in order to select the best variables for predicting the level of walking ability. The accuracy of these models ranged from 72.5% to 82.5%.

Conclusion By using SVM model with four variables (age, FCI, level of amputation, and mobility at admission) we are able to predict the level of ambulation with a prosthesis in lower limb amputees with high accuracy.

Keywords: amputation; rehabilitation; recovery of function; support vector machines

INTRODUCTION

Lower limb amputation represents one of the classical rehabilitation problems amenable to intervention by a physiatrist. Because of the aging of the population and the increased incidence of diabetes, the number of amputations is expected to increase in the future [1].

One of the crucial moments in the period after lower limb amputation is the decision whether the patient will be a proper candidate for a prosthesis. This decision is not always easy, and factors that could predict rehabilitation outcome in these patients are only partially understood [2]. The physiatrist, the therapist and especially the health insurance are all interested in the costs of prosthetics and rehabilitation treatment on the one hand, while, on the other hand, patients and their families are interested in the highest possible functional outcome after major limb amputation. In Serbia, after lower limb amputation, patients are examined by a physiatrist, who is responsible for prescribing a prosthesis. This examination often takes place several months after the amputation due to medical or administrative reasons. The number of patients that will be able to walk with a prosthesis after lower limb amputation vary among authors in the range of 50–90% [3, 4, 5].

Many factors potentially influence walking ability with a prosthesis. Patients with dysvascular amputations often have diabetes mellitus, and both conditions are associated with the reduction of physical and cognitive capacities. These reductions can affect the prosthetic use [6]. The influence of comorbidities on functional outcome in patients with lower limb amputation is questionable. There is often a lack of clear connection between comorbidities and walking ability [7–11]. Lower limb amputation constitutes more than 95% of all amputation, while the most common level is transtibial [12, 13]. It is generally accepted that the functioning of these patients is worse in higher amputation level and in older age [6, 8]. Information on influence of gender on functionality, on the other hand, is relatively scarce [14]. It is generally accepted that men are more often affected by lower limb amputation [15]. Whether gender has any influence on functional outcome in these patients remains an open question. While some researchers have found lower functionality in women, others did not find significant difference [9, 14]. Residual limb hip extensor muscle strength was shown to be a strong predictor of the walking distance of these patients [7], while the presence of residual limb contracture was negatively linked

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to prosthetic ambulation in the literature [7, 9]. We must not underestimate the influence of social support on the functional outcome of lower limb amputees [8]. Patients with good social support appear to show greater mobility after amputation [16].

Identification of predictive factors for walking ability in these patients is very important in order to define a patient's potential and realistic rehabilitation goals. Most of the articles used linear or logistic regression models, which were formed and analyzed on one sample of patients, i.e. regression models were not tested on unknown patients [6, 7, 8, 10, 14]. On the other hand, some more advanced regression models could be useful in the analysis of this kind of data which are very "noisy", uncertain or incomplete.

In the last few decades, the applications of machine learning and optimization methods in the procedures of medical diagnoses and prognosis have become very common because of their efficiency in cases where only small amount of data are available or they are incomplete or noisy.

In this paper, we used a relatively new method of machine learning for making the mathematical model for predicting the level of walking ability with a prosthesis after lower limb amputation. We have proposed a prediction model based on support vector machines (SVMs) [17], where a set of input variables was optimized using global optimization algorithm named genetic algorithm (GA) [18]. SVM is a soft computing method which refers to learning from experimental data and human knowledge by transferring them into analytical models. SVM is a learning method, which overlaps with statistics in many ways, but it's not a statistical method. SVM acts as one of the best approaches of data modeling, based on the principle of structural risk minimization, avoiding local minima and handling large amounts of data very well. In recent years, SVM has found application in many wide medical applications including digital imaging [19], medical signal processing [20], and various prediction problems [21, 22].

OBJECTIVE

The objective of this study was to investigate whether variables determined at the beginning of rehabilitation process are able to predict the ability of lower limb amputees to walk with a prosthesis after treatment using SVM models.

METHODS

This study was designed as a retrospective clinical case series. It encompassed patients with lower limb amputation who underwent prosthetic rehabilitation treatment at the Medical Rehabilitation Clinic of the Clinical Centre of Vojvodina in the city of Novi Sad, in the period from 2000 to 2009. We searched the archive in the given period with the key diagnosis of "amputation." All medical records found underwent a thorough review. Inclusion criteria were as follows: unilateral transtibial or transfemoral amputation, patients who received their first prosthesis. We

excluded patients who did not get prosthesis, patients who underwent prosthetic fitting and gait training earlier, patients who underwent prosthetic fitting and gait training in outpatient manner, patients with bilateral amputation (toe amputation excluded), patients who due to the complications could not finish prosthetic fitting and gait training, and patients with incomplete medical documentation.

We collected data about the level of amputation (transfemoral/transtibial), age, gender, the period from amputation to prosthetic rehabilitation, the cause of amputation (dysvascular, trauma, other), the number of comorbid conditions was assessed by Functional Comorbidity Index (FCI) [23]. Two physicians scored the presence of 18 comorbidities independently, while in case of a disagreement, each diagnosis was achieved through consensus. We noted the presence of phantom pain, the presence of hip or knee extension restriction in residual limb which was defined as a hip extension less than 0° or a knee extension less than -10° measured with classical goniometer. Residual limb hip extensors strength was graded according to manual muscle testing. Furthermore, we identified whether patients had a partner or not. We also recorded the mobility level of these patients at admission and grouped our findings into three different levels: the first consisted of those patients who were ambulatory with crutches or a walker even outdoors; the second consisted of the patients who were able to walk with crutches or a walker only indoors and needed a wheelchair for outdoors mobility, and the third were the patients who were not able to ambulate with crutches or a walker and needed a wheelchair all the time.

At the end of the rehabilitation treatment, the patients were divided into three functional levels: the patients who were unable to walk independently with a prosthesis, the patients who were able to walk independently with a prosthesis only indoors, and finally, the patients who were able to walk with a prosthesis outdoors.

The data were summarized descriptively with frequency and percentage tables, Student's t-test was used to compare age, FCI, and the time from amputation until prosthetic rehabilitation, while χ^2 test was used for comparisons of functional outcome categories and the level of amputation for females and males. $P \leq 0.05$ was considered statistically significant.

SVMs were used for creating mathematical models for predicting the level of walking ability with a prosthesis.

SVM learning algorithm (classifier) attempts to learn the input-output relation by using a training data set $X = \{ \{x_i, y_i\}, i = 1, \dots, m \}$, where the inputs x are n -dimensional vectors and the labels y are discrete. There are two phases when applying supervised learning algorithms for problem-solving. The first phase is the so-called learning phase where the learning algorithms design a mathematical model of a dependency, classifiers (in a classification i.e., pattern recognition) based on the training data given. The second phase is the test and/or application phase. In this phase, the models developed by the learning algorithms are used to predict the outputs y of the data which are unseen by the learning algorithms in the learning phase. Before an actual application, the test phase is always carried out for checking the accuracy of the models developed in the first phase.

GA represents a robust optimization method based on elementary mechanisms of evolution. GA imitates processes of nature selection and reproduction in order to solve a certain optimization problem. The first point of such mathematical evolution is the population of n individuals where every individual represents a potential solution. Every individual has its measure of adjustment, i.e. in mathematical sense, the value of optimization criteria. Using operators like selection, crossover and mutation GA attempt, through iterations (generations of population), we achieved the best value of optimization criteria function.

RESULTS

We identified 373 patients with 'amputation' as the primary diagnosis, 110 of which were excluded from this

study for the following reasons: 30 patients were bilateral lower limb amputees, 32 patients underwent a prosthetic fitting and training earlier, 27 patients did not receive a prosthesis, nine patients were excluded due to an incomplete medical documentation (there were no data about the rehabilitation outcome), 10 patients were excluded due to complications which prevented further rehabilitation, and two were excluded because the amputation diagnosis referred to upper extremities. A total of 263 patients were included in the study. The characteristics of these patients are given in Table 1.

There were no significant differences between men and women in terms of the average age (60.56 vs. 62.09; $t = -1.01$; $p = 0.313$), FCI scores (2.16 vs. 2.33; $t = -0.149$; $p = 0.881$), and the period from the amputation to prosthetic rehabilitation (185.57 vs. 189.36; $t = -1.048$; $p = 0.295$). Although women suffered from transfemoral

Table 1. Patients' characteristics and the prosthetic rehabilitation outcome

Characteristics		Value
Age (years)	Mean \pm SD	60.82 \pm 9.27
	Range	24–82
Gender	Male	218 (83%)
	Female	45 (17%)
Cause of amputation	PAD (with or without DM)	237 (90.1%)
	Trauma	16 (6.1%)
	Other	10 (3.8%)
Amputation level	Transtibial	93 (35%)
	Transfemoral	170 (65%)
Period from amputation to prosthetic fitting and training (days)	Mean	186.22
	Range	28–973
Functional comorbidity index (FCI)	Mean \pm SD	2.19 \pm 1.03
	Range	0–5
The most common comorbidities from FCI	PAD	236 (89.7%)
	DM	172 (65.4%)
	Myocardial infarct	37 (14.1%)
	Upper gastrointestinal disease (ulcer, hernia, reflux)	30 (11.4%)
	Visual impairment (cataract, glaucoma)	23 (8.8%)
	Stroke or TIA	22 (8.4%)
Phantom pain	Yes	52 (27.8%)
	No	135 (72.2%)
	Missing data	76
Partner	Yes	192 (75.6%)
	No	62 (24.4%)
	Missing data	9
Restriction of hip or knee extension	Yes	38 (15.5%)
	No	207 (84.5%)
	Missing data	18
Residual limb hip extensor strength according to MMT	Grade 2	74 (29.2%)
	Grade 3	167 (66.0%)
	Grade 4	12 (4.7%)
	Missing data	10
Mobility at admission	Ambulatory with crutches / a walker outdoors	132 (50.2%)
	Ambulatory with crutches / a walker indoors only, a wheelchair outdoors	56 (21.3%)
	Mobile only with a wheelchair	75 (28.5%)
Functional outcome after rehabilitation	Unable to walk	18 (6.8%)
	Walk indoors only	71 (27%)
	Walk outdoors	174 (66.2%)

Values are presented as mean value \pm standard deviation and as the number of patients with percentage (%).

PAD – peripheral arterial disease; DM – diabetes mellitus; TIA – transient ischemic attack; MMT – manual muscle testing

level of amputation more often, this difference was not significant [136 (62.4%) vs. 34 (75.6%), $\chi^2 = 2.831$; $p = 0.092$]. On the other hand, men reached significantly higher functional level at the end of rehabilitation treatment ($\chi^2 = 6.672$; $p = 0.036$) (Table 2).

As expected, the walking ability of the patients with transtibial level of amputation with a prosthesis was much

better than in the case of the patients with transfemoral level ($\chi^2 = 14.047$; $p = 0.001$) (Table 3).

In order to create optimal SVM model for predicting the level of walking ability after lower limb amputation, we optimized a set of input variables using GA. Every individual of GA population represents a "bit mask" which determines which variable will be used in the SVM model.

Table 2. Functional outcome levels at the end of the rehabilitation treatment in men and women

Gender		Unable to walk with a prosthesis	Walk with a prosthesis indoors only	Walk with a prosthesis outdoors	Total	χ^2	p
Men	N	12	55	151	218		
	%	5.5	25.2	69.3	100.0		
	$\Sigma\%$	66.7	77.5	86.8	82.9		
Women	N	6	16	23	45		
	%	13.3	35.6	51.1	100.0		
	$\Sigma\%$	33.3	25.5	13.2	17.1		
Total	N	18	71	174	263		
	%	6.8	27.0	66.2	100.0		
	$\Sigma\%$	100.0	100.0	100.0	100.0		

N – number of patients

Table 3. Level of amputation and functional outcome at the end of the rehabilitation treatment

Amputation level		Unable to walk with a prosthesis	Walk with a prosthesis indoors only	Walk with a prosthesis outdoors	Total	χ^2	p
Transtibial	N	5	13	75	93		
	%	5.4	14.0	80.6	100.0		
	$\Sigma\%$	27.8	18.3	43.1	35.4		
Transfemoral	N	13	58	99	170		
	%	7.6	34.1	58.2	100.0		
	$\Sigma\%$	72.2	81.7	56.9	64.6		
Total	N	18	71	174	263		
	%	6.8	27.0	66.2	100.0		
	$\Sigma\%$	100.0	100.0	100.0	100.0		

Table 4. Selected variables and accuracy of SVM classifiers on test data

Variables	Number of selected variables					
	4	5	6	8	10	11
Age	×			×	×	×
Gender		×	×	×	×	×
Period from amputation to prosthetic fitting and training						×
Partner		×		×	×	×
Cause of amputation			×	×	×	×
Amputation level	×		×		×	×
FCI	×	×	×	×	×	×
Diabetes mellitus				×	×	×
Residual limb hip extensor strength			×	×	×	×
Restriction of hip or knee extension		×	×	×	×	×
Mobility at admission	×	×			×	×
Accuracy	%	82.5	77.5	77.5	77.5	72.5
	Predicted/Actual	33/40	31/40	31/40	31/40	31/40

FCI – Functional Comorbidity Index

Table 5. Predicted versus actual functional outcome levels

ACTUAL	PREDICTED			
	Unable to walk	Able to walk with a prosthesis indoors only	Able to walk with a prosthesis outdoors	Total
Unable to walk	0	1	0	1
Able to walk with a prosthesis indoors only	0	9	3	12
Able to walk with a prosthesis outdoors	0	3	24	27
Total	0	13	27	40

Optimization criteria was the accuracy of classification on set test data. In order to compare the influence of different variables and a different number of variables with the accuracy of prediction models, we created several SVM models (Table 4).

Interestingly, our first model with four variables was the most accurate one. That model included age, amputation level, FCI, and mobility at admission to the Clinic, and successfully predicted 33 of 40 functional outcome levels (Table 5). Gender, FCI, and residual limb contracture were the most frequent variables in our models, while the period from amputation to prosthetic fitting and training was present in only one model (the one which included all variables).

Our model failed to predict the functional level for a patient who was unable to walk with a prosthesis, while the accuracy for those able to walk with a prosthesis indoors and outdoors was 69.2% and 88.9%, respectively.

DISCUSSION

The prediction of walking ability after lower limb amputation is crucial in the rehabilitation process of these patients. It represents the base for the prosthesis prescription. The purpose of this study was to explore the possibilities of functional level prediction in these patients. Although it is clear that walking ability with a prosthesis depends on more than one factor, the predominant predictors are still vague.

In our analysis, we recognized two groups of significant variables. The first group consisted of those variables that were used in the SVM model which was the most accurate (with four variables), and the second consisted of variables that were selected for the majority of the models. We assumed that these variables were the most important for our prediction and we took a closer look at them.

During the 10-year period of our research, the majority of patients with lower limb amputation were men. This was similar to other researches [24, 25]. In the literature, however, data about gender influence on prosthetic rehabilitation outcome is scarce [14]. Lefebvre and Chevan [26] found transfemoral level of amputation more often in women, which could explain lower functional levels in female patients. In our study, women suffered from transfemoral level of amputation more often, although this difference did not reach any significance. On the other hand, men had a significantly higher walking ability with a prosthesis. It is well known that women reach lower walking speed and lower step length in comparison to men [27, 28, 29]; therefore, we can presume that the difference in gender will be more profound after lower limb amputation. Our models included gender in five of six models, which indicates that gender could be considered as a predictor for ambulation with a prosthesis.

People who lived with their partners showed increased social support, which could improve the outcome after lower limb amputation [16]. The presence of a partner was an important variable in our study as well. It was present in four SVM models.

Age was an important predictor for walking ability after lower limb amputation in our study, since it was selected in the first model with the highest accuracy. This is consistent with other researchers [7, 30].

We found that transfemoral level of amputation was the most common level in our study, which was inconsistent with other researchers, who argued that the transtibial level of amputation was the most frequent one [24, 31]. The reason for this distinction probably lies in the fact that patients reach vascular surgeons too late in our country; in other words, their primary disease reaches the advanced stage and the level of amputation has to be higher. It is of a great importance to preserve knee joint, if possible, keeping in mind functional outcome of these patients [32]. Our study agrees with these findings, highlighting that the level of amputation was an important factor in the prediction, given it was part of the most accurate model.

Walking with a prosthesis requires higher energy consumption than walking with both intact lower extremities [33]. Comorbidities such as peripheral artery disease, myocardial infarcts, angina pectoris, heart failure or diabetes reduce cardiovascular capacity in these patients, and also the walking ability with a prosthesis. In our study, each of the six models included FCI, which was interpreted as having a great significance for this variable, although we were not sure whether it was independent of the other variables or not. It would be possible that FCI emerging among other variables consisted of unbalanced data if it was collected with the lowest degree of error. However, De Laat et al. [34] in their study found that FCI was connected to the independence of lower limb amputees in climbing stairs. FCI was not used too often in the literature, probably because it is a relatively new index. Its orientation to function is crucial, and we are expecting a larger number of studies using this index in the future.

Some authors argue that the presence of contractures could be a negative prognostic factor for successful prosthetic ambulation [9]. Our findings were similar, and the presence of the residual limb restriction of hip or knee extension was included in five of six models. Raya et al. [7] found that residual limb hip extensors strength is a very important predictor of walking with a prosthesis, which is in line with our findings.

The functional mobility after lower limb amputation is an important predictor of rehabilitation outcomes [6]. We divided mobility at admission in three groups according to the patients' ability to use crutches. This variable was included in four of six models, including the most accurate one.

Our models predicted walking ability after prosthetic rehabilitation with high accuracy. It should be emphasized that these results were achieved on samples unknown to our models. Every model was tested on an unknown data set – in other words, we randomly chose 40 patients whose data was excluded from the training set when the models were formed. Then we tested given SVM models on 40 previously unseen patients' data. As far as we know, this was the first study where SVMs were used in order to predict functional outcome after lower limb amputation.

In addition, quality of data could be analyzed in a mathematically more formal way. This means that the best

prediction results were obtained with only four input arguments (82.5%), while the accuracy of prediction decreases with more arguments in input vector (Table 4). In our case, a relatively small number of input arguments (maximum 11) could not lead to curse of dimensionality problem, i.e. the model complexity. We assume that the quality of the collected data directly leads to unbalanced data sets, which presents a challenge when training a classifier and SVMs. Therefore, we propose GA optimization approach to select features (input parameters), which gets the highest classification accuracy.

Despite meeting our goals, this study had limitations which are characteristic of a retrospective analysis. The quality of data relied on the reliability of medical documentation. Therefore, certain limitations in our study warrant further consideration. Firstly, manual muscle testing and measurement of joint range of motion was performed by many therapists (more than 10), which could put the reliability of these measurements in question. Secondly, similarly to all retrospective studies, we also had a prob-

lem with the missing data and we did not include the factors such as phantom pain in further analysis due to the fact that a substantial number of patients' histories were missing this information. Similarly, we could not identify enough data about cognitive and social factors which could be important predictors of the functional outcome in these patients. Despite all aforementioned facts, our models predict functional outcome with high accuracy.

CONCLUSION

By using an SVM model with four variables (age, FCI, level of amputation, and mobility at admission) we can predict the level of ambulation with a prosthesis in lower limb amputees with high accuracy.

For future researches we suggest using new variables, such as cognitive, social variables, and phantom pain in order to estimate walking ability with a prosthesis more precisely.

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Фактори који утичу на способност ходања уз помоћ протезе код болесника после ампутације ноге

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КРАТАК САДРЖАЈ

Увод Идентификовање фактора који могу да предвиде способност за ход уз помоћ протезе након ампутације доњих екстремитета веома је важно како би се дефинисали потенцијали пацијената и поставили реални рехабилитациони циљеви.

Циљ рада Циљ ове студије био је да се испита, уз помоћ алгоритама базираних на потпорним векторима (*SVM*), да ли фактори утврђени на почетку рехабилитационог процеса могу да предвиде исход рехабилитације.

Методе рада Ово истраживање дизајнирано је као ретроспективна клиничка серија случајева током које су анализирани историје болести пацијената. Исход је дефинисан као тростепена способност хода уз помоћ протезе. У формирању модела за предвиђање коришћени су *SVM*.

Резултати У студију је укључено 263 пацијента просечне старости $60,82 \pm 9,27$ година. У формиранње *SVM* модела укључено је једанаест варијабли: старост, пол, узрок ам-

путације, ниво ампутације, период од ампутације до протетичке рехабилитације, функционални коморбидитетни индекс (*FCI*), присуство шећерне болести, присуство партнера, ограничена екстензија кука или колена резидуалног екстремитета, мишићна снага екстензора резидуалног екстремитета, мобилност при пријему. Формирано је шест модела са 4, 5, 6, 8, 10 и 11 варијабли. Генетски алгоритми (*GA*) коришћени су да би се одабрале најбоље варијабле за предвиђање нивоа оспособљености за ход са протезом. Прецизност модела кретала се од 72,5% до 82,5%.

Закључак Користећи *SVM* модел са четири варијабле (старост, *FCI*, ниво ампутације и способност кретања при пријему), можемо у високом проценту предвидети ниво способности за ход уз помоћ протезе особа са ампултацијом доњих екстремитета.

Кључне речи: ампултација; рехабилитација; опоравак функције; потпорни вектори