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REVIEW ARTICLE

Application of control strategies and machine learning techniques in prosthetic knee: a systematic review

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Abstract

This systematic review focuses on control strategies and machine learning techniques used in prosthetic knees for restoring mobility of individuals with trans-femoral amputations. Review and classification of control strategies that determine how these prosthetic knees interact with the user and gait strategy inspired algorithms for phase identification, locomotion mode, and motion intention recognition were studied. Relevant studies were identified using electronic databases such as PubMed, EMBASE, SCOPUS, and the Cochrane Controlled Trials Register (Rehabilitation and Related Therapies) up to April 2021. Abstracts were screened and inclusion and exclusion criteria were applied. Out of 278 potentially relevant studies, 65 articles were included. The specific variables on control approach, control modes, gait control, hardware level, machine learning algorithm, and measured signals mechanism were extracted and added to summary table. The results indicate that advanced methods for adapting position or torque depiction and automatic detection of terrains or gait modes are more commonly utilized, but they are largely limited to laboratory environments. It is concluded that a correct combination of control strategies and machine learning techniques will enable the improvement of prosthetic performance and enhance the standard of amputee's lives.

Keywords Algorithm · Control strategies · Gait · Machine learning · Prosthetic knee

1 Introduction

The human knee is the largest and perhaps the most complex joint in the body. The knee plays a significant role during gait. It supports body weight and deceleration during the stance phase (Nordin and Frankel 2001). It acts like a spring which is evident from the linear relationship of moment–angle during stance phase. The positive impedance characteristics of the knee assist it during stance phase (Cherry et al. 2006). It has been observed that gait characteristics vary between able-bodied subjects and trans-femoral (TF) amputees due to stability of the prosthetic knee (Silver-Thorn and Glaister 2009; Mohanty et al. 2020a, b). Knee buckling during stance results due to instability and leads to gait deviations with increased energy consumption (Silver-Thorn and Glaister 2009; Romo 2000). Patient's abilities and functional goals are considered to determine suitable prosthetic knee for smooth and reliable gait for each individual (Romo 2000; Michael 1999), and therefore, gait analysis has been used to provide a valid tool to correlate with experimental results (Mohanty et al. 2020a; b). Prosthetic knee is stabilized by inherent mechanical stability of the mechanism itself and the voluntary stability by hip extensors of TF amputee (Radcliffe 1977, 1994; Oberg 1983). However, a smooth transition from stance to swing phase is more difficult function to replicate (Radcliffe 1977; De Vries 1995; Andrysek et al. 2004).

Based on control, lower limb prostheses can be categorized into passive, semi-active, or variable damping and powered or intelligent (Geng et al. 2010). Passive prostheses require positive power at the knee and ankle joints and present with asymmetrical gait with increased energy consumption (Eilenberg et al. 2010). In addition, it is not

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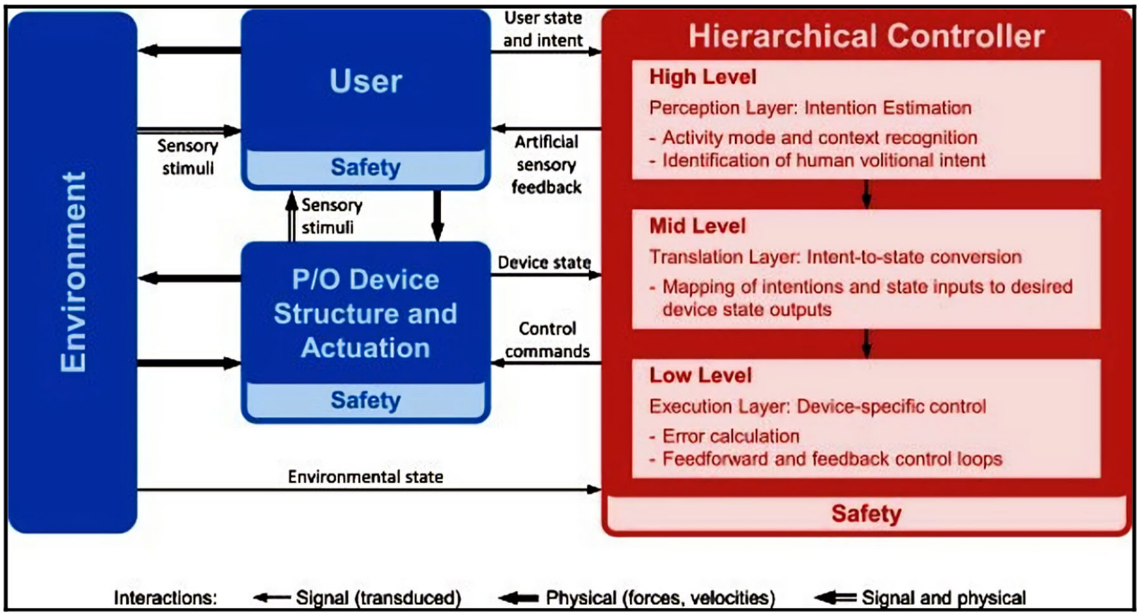

Fig. 1 Generalized control framework for lower limb prosthesis (Tucker et al. 2015)

possible for the individual with an amputation to generate positive power at the knee and ankle joints of a passive prosthesis due to the fact that there is no direct control over these prosthetic parts. Semi-active or auto-adaptive (Sawers and Hafner 2013) prostheses modulate damping levels to improve the knee stability and cadence responsiveness but cannot produce positive power (Martinez-Villalpando and Herr 2009). Active or intelligent prostheses are coupled to human gait through electronic systems capable of user's intent recognition and can produce necessary positive power, and, therefore, restore locomotion and other activities of daily living more efficiently and naturally (Liu et al. 2014, Torrealba et al. 2010). Robotic technology is applied predominantly for troubleshooting of current active prosthetic controllers (Hargrove et al. 2013a; b). They recognize user's motion intentions and proceed to aid in movements with least perceptual disturbances. Thus, an ingenious and communal prosthetic controller must begin with knowledge of the human controller (Tucker et al. 2015). Figure 1 shows a generalized working framework for lower limb prosthesis and Fig. 2 shows the general architecture for control systems with gait phase identification.

In spite of significant developments in active and semi-active knee devices, potential issues like development of control strategies, portable power supplies, lightweight actuators, and high-efficiency transmissions, etc. need improvements (Romo 2000). An overview of control strategies in lower limb prosthesis has been provided by several review articles (Fluit et al. 2020; Berry 2006). Authors have focused on control strategies with focus on ankle prostheses (Jiménez-Fabián and Verlinden 2012), actuator design issues (Pieringer et al. 2017; Windrich et al. 2016), and corresponding control strategies (Lara-Barrios et al. 2018; Ferreira et al. 2015), yet a clear and in-depth overview is lacking. Previous studies have failed to separate the control methods from hardware and implementation details. The various control approaches of prosthetic knee devices to enhance the locomotion of subjects with trans-femoral amputations are thoroughly addressed in this review. In contrast to the existing literature reviews, a stronger attention is placed on the control methods.

Machine Learning (ML) has been reported in the literature as the study of how computer algorithms (i.e., machines) can "learn" complex relationships or patterns from empirical data (Wang and Summers 2012) and, hence, produce (mathematical) models linking an even large number of covariates to some target variable of interest (Obermeyer and Emanuel 2016). Application of a machine learning technique and method to prosthetic knee systems has been explored which works with the help of input of different sensors and apply sophisticated algorithms to give a better gait pattern to an amputee. Currently, machine learning algorithms are designed to recognize or to predict a locomotion mode to automatically adapt the behavior of prosthetic knees. In spite of this, a clear review of commonly used machine learning approaches and control algorithms for recognition and prediction of prosthetic knee functions is not found in the literature to authors' knowledge.

Ankle and foot prostheses are not taken into consideration for this review. The main research question that needs to be addressed in this review was to explore and study of what approaches are being used in the literature to control

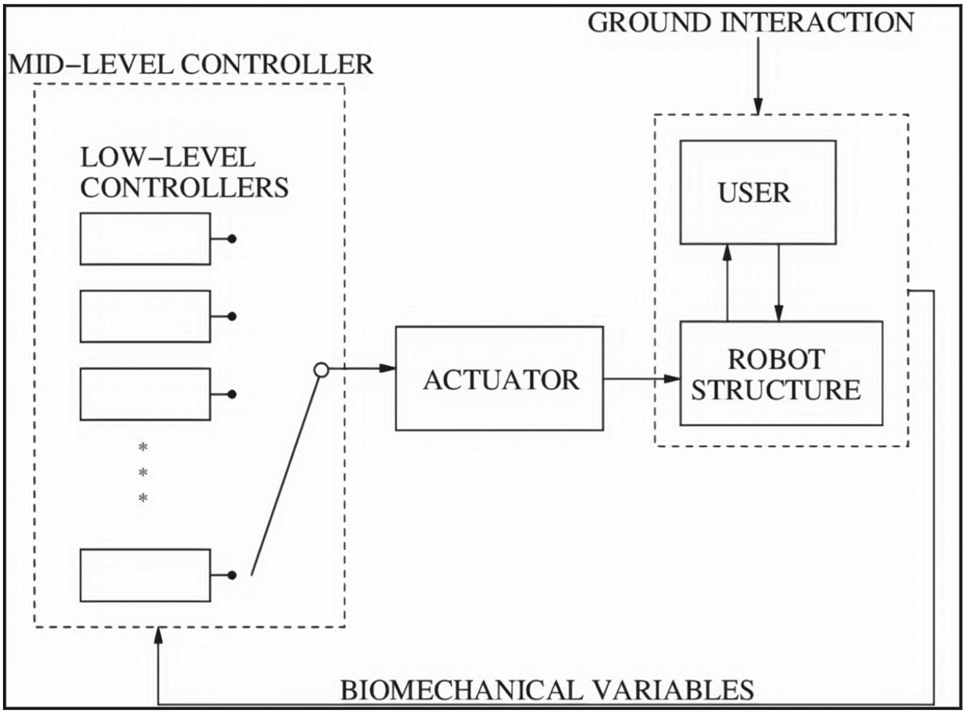

Fig. 2 General architecture for control systems with gait phase identification (Varol et al. 2008)

prosthetic knee devices for directly assisting gait in subjects with trans-femoral amputation? This contribution provides a review of main control strategies and machine learning techniques proposed for prosthetic knees in restoring mobility of individuals with trans-femoral amputations. It includes an overview and comparison of essential technical details with special attention being paid to the algorithms employed for motion intent recognition, different walking adaptation, gait phase identification, and generation of walking patterns for better understanding through a clear presentation. The paper is arranged as follows. Most common control strategies applied in powered lower limb prosthetic devices are discussed in Sect. 3. In Sect. 4, a brief comparison of the presented literature review is presented. The conclusions are presented in Sect. 5.

2 Methods

This section is organized as literature search, study selection, data extraction, data synthesis, and analysis to show the procedure involved in systematic review.

A. Literature search
This systematic review is reported following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines. This review focuses on Machine Learning Techniques and Control Strategies used in prosthetic knees. Relevant articles were collected by searching databases like PubMed, SCOPUS, EMBASE, and the Cochrane Controlled Trials Register (Rehabilitation and Related Therapies) up to April 2021. The keywords such as amputation, trans-femoral, prosthetic knee, machine learning, control algorithms, and control strategies were used for literature search. All results were checked for any duplication. Moreover, the reference lists of all searched studies were screened with to reveal any additional eligible studies.

B. Study selection
The following topics were chosen for review:

1. Control strategies of prosthetic knee devices.
2. Applications of machine learning techniques and control algorithms of prosthetic knee mechanism.
   Inclusion criteria set for selection of articles are as follows:

a. Control strategies intended for active and semi-active knees.
b. Algorithms for motion intent recognition, different walking adaptation, gait phase identification, and generation of walking patterns (to determine the required joint kinematics for performance of activities).
c. Control algorithms for knee and hip devices.
d. Experimental and numerical results for understanding the behavior of the algorithms (an approach to algorithm design and analysis).
   Papers were excluded for application of endoprosthesis and in case of non-fulfillment of inclusion

criteria. Any published systematic reviews and meta-analyses were excluded.

Two investigators (R.K.M. and S.S.) independent from one another, screened the title first, followed by abstracts identified in the database searches. R.K.M. was responsible for reviewing abstracts identified in PubMed, EMBASE, and S.S. reviewed abstracts from SCOPUS and the Cochrane Controlled Trials Register databases (Rehabilitation and Related Therapies). These two investigators then applied the inclusion and exclusion criteria to the abstracts. Abstracts which did not meet the inclusion criteria were excluded and the reason for exclusion was recorded. Duplicate articles were removed. The remaining full-length articles were then retrieved and reviewed by these two reviewers to further determine whether the study met inclusion or exclusion criteria. A senior investigator (R.C.M.) verified and made the final decision.

C. Data extraction

Articles were assessed for their relevance to the implementation of control strategies and machine learning algorithms in prosthetic knees. The evaluation of papers was based on:

a. description of hypotheses and objectives, including study designs,
b. sufficient description of control strategies and machine learning approaches to extract essential technical details; and
c. report of results with enough details to correlate with conclusions.

The variables like control approach, control modes, gait control, hardware level, machine learning algorithm, and measured signals mechanism of prosthetic knee centered on restoration of mobility in amputees were drawn out from the included studies. This was done by several authors (R.K.M. and R.C.M.), independent from each other. All items were validated by all authors.

D. Data synthesis and analysis

Specific variables on control strategies and machine learning techniques were extracted and added to the summary table. These extracted features were used for the analysis. Summary table was used to group studies according to themes. During screening, grouping of articles was performed based on desired parameters. The results of this study were derived from a systematic review approach where all accessible articles were comprehensively analyzed and conclusions were made for best quantitative prediction.

3 Results

Flowchart showing results from the literature search is represented in Fig. 3. The search yielded abstracts from 278 published works. A total of 65 studies were included in this systematic review after applying inclusion and exclusion criteria.

A. Control strategies

The control strategies of prosthetic knee devices can be subdivided into three parts: high-, middle-, and low-level control. High-level control is accountable for recognizing the user's intent of locomotion and supported signals from the user, environment, and the device. Mid-level controller receives these signals and translates the user's intentions to a desired output state for the device. The directive from mid-level controller is delegated to the low-level, which represents the device-specific control loop that accomplishes the specified motion (Tucker et al. 2015). This is called the concept of the hierarchical behavior controller (Fukuda and Hasegawa 2004).

The control approaches can be divided into four categories: echo control, finite-state impedance control, electromyography-based control, and Central Pattern Generator-based control.

An echo control (Joshi et al. 2010; Grimes et al. 1977; Wu et al. 2011) synchronizes joint position of prosthesis based on the motions of the intact limb, but the implementation of response is not instantaneous.

A finite-state impedance control (Eilenberg et al. 2010; Sup and Goldfarb 2008; Sup et al. 2009a, b; Liu et al. 2014; Lambrecht and Kazerooni 2009; Martinez-Villalpando and Herr 2009; Lawson et al. 2013; Sup et al. 2009) is the commonest and is based on generation of different joint torques around knee and ankle which are applied in each finite state of the locomotion. Calculation of impedance model of each joint was done using a virtual non-linear spring and damper.

An electromyography-based control (Huang et al. 2009; Wu et al. 2011) uses EMG signals to compute the control inputs for the controller. An implicit agonist–antagonist linear muscle model is utilized to compute torque application at prosthetic knees. Thus, there is a proportional relationship between measured muscle signal and torque generation for control of prosthesis.

A central pattern generator (Torrealba et al. 2012; Torrealba et al. 2010; Guo et al. 2010; Duysens and Forner-Cordero 2019) uses biologic neural grid. They are modulated by basic sensory signals which are being modeled and extensively studied. These controls can produce synchronized periodic patterns of activities. These systems have the advantages of smooth trajectory modulation, low estimated cost, and easy feedback integration.

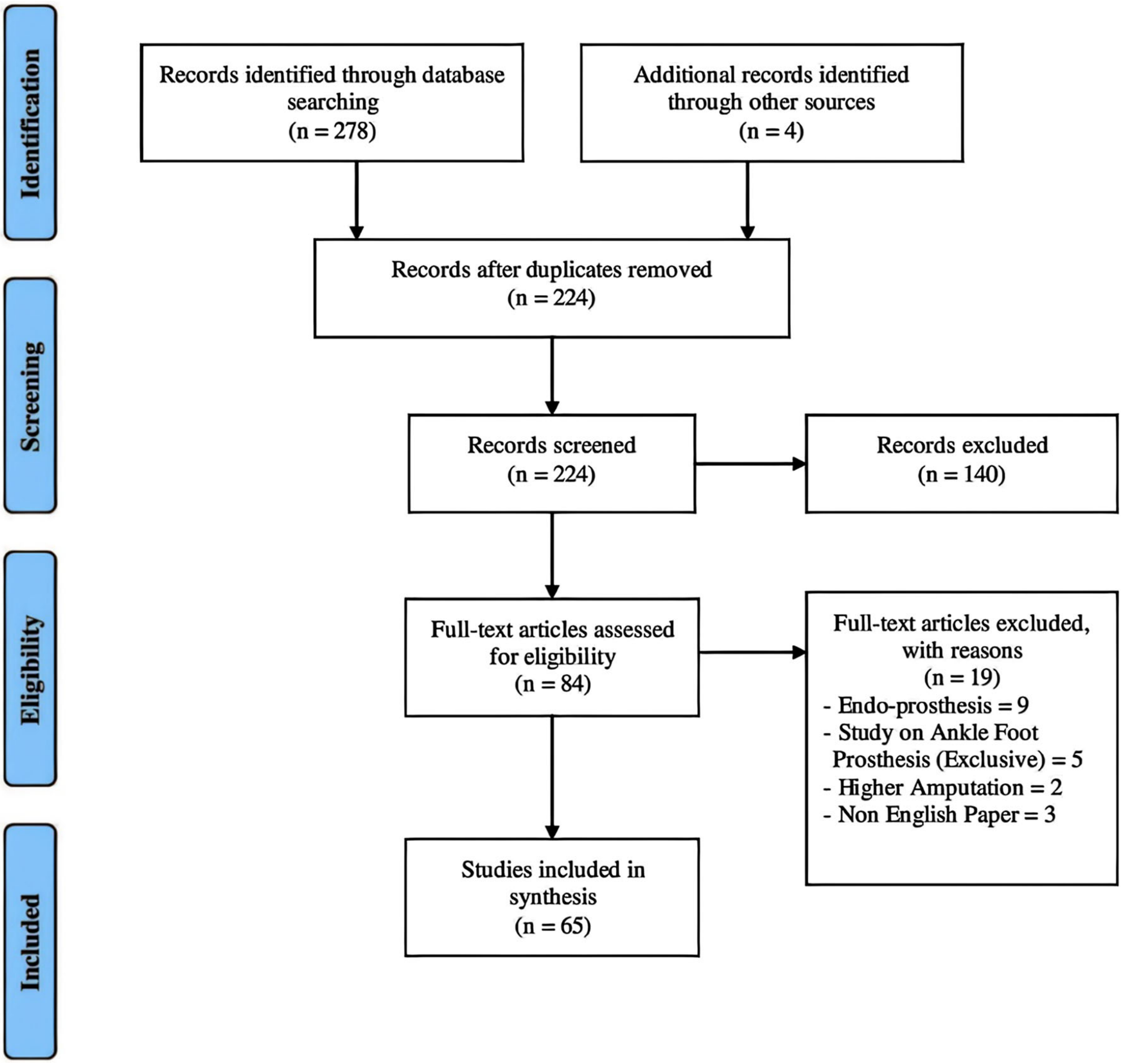

Fig. 3 PRISMA flowchart of the included studies

B. Machine learning techniques and control algorithms
Machine learning uses various algorithms to realize gait harmony, movement analysis, and stumble control. Some commonly used techniques are: control logic, Intent detection algorithm, Genetic algorithm, mathematical logic-based classifier, Expectation maximization algorithm, and Impedance control algorithm.

Control algorithm (Awad and Abouhussein 2016; Tucker et al. 2015) is employed in which the controller supervises the joint position trajectory, however the output of those algorithms isn't always guaranteed.

Intent detection algorithm (Varol and Goldfarb 2007; Zhang and Huang 2013; Bhakta et al. 2020) is worn out two ways: unsupervised and supervised machine learning. Supervised learning uses the method of predicting a model on a trained range of inputs learning function to map the known output, which discovers the pattern of latest sets of information. The algorithm of unsupervised learning finds an answer to unknown or unlabelled data which does not require any reasonable supervision from humans.

Genetic algorithm (Martinez-Villalpando and Herr 2009; Zhang et al. 2019; Amador et al. 2012) may be a search-based optimization technique supported the principles of Genetics and survival of the fittest. It is frequently accustomed, find optimal or near-optimal solutions to difficult problems. The solutions are obtained from the big datasets which sensors have accumulated over a time span in response to situation-based demand from prosthesis.

Fuzzy logic (Alzaydi et al. 2011; Hong-liu et al. 2008) is an approach to variable processing that permits for multiple values to be processed through the identical variable. It strives to unravel problems with an open, non-specific range of knowledge to produce possible groups of precise conclusions. It works on the logic of grouping amputees, and hence, the input file is classed according to logic created within the algorithm.

Expectation maximization algorithm (Fessler 1994; Nandi 2008; Varol et al. 2008; Varol et al. 2009) is employed in an energetic knee where the body of data is somewhat congregated. It maximizes the probable data space function which is not measured instead of maximizing the function of the unfinished or measured data with improved efficiency and accuracy.

Impedance control algorithm (Varol and Goldfarb 2007; Herr and Wilkenfeld 2003; Duysens and Forner-Cordero 2019) is the most commonly used control strategy (El-Sayed et al. 2014) within which the torque generated is tailored to the produced knee angle. It ensures that the knee joint produces sufficient torque that is worthy for every phase of gait (Martinez-Villalpando and Herr 2009). Table 1 summarizes the control strategies and machine learning techniques used in prosthetic knee control.

4 Discussion

The aim of this review paper was to overview the control strategies and machine learning techniques for prosthetic knee applications for restoring and improving gait performance. An attempt was made to enlighten on the basic concepts used in knee control including control approaches and modes, hardware platforms, machine learning algorithms, measured signals, and type of prosthesis.

Advancements in electronics and continuous research work have led to the development of cutting-edge to intelligent knee prostheses to improve the quality of life of amputees. The most common control strategies used by these kinds of prostheses are finite-state ones which are also noted as soft control. There are a group of pre-declared rules combined with information about specific criterion associated to natural and prosthetic gait available in a system directory. Control signals are sent to the prosthetic actuator for the necessary output action. Sensors placed at different tactical points on the body surface provide input signals which are processed through a processor. The processor compares these input values with the information in the directory, and attempts to recognize the current instant and activity of involvement during gait cycle. Each of these instants is correlated with a state, which is again linked with a pre-declared rule. This finally transforms into a control action through a prosthetic actuator. However, these controls are more complex, less robust, and lack real-time implementation of desired functions (Zlatnik et al. 2002). CPGs have been intended to spot users' purpose during gait cycle and generate an algorithm that replicates bipedal locomotion (Gupta and Anand 2005). In particular, researchers have always been fascinated by electro-myographic signals. It is documented that the information transferred by these signals is useful to identify user intention and subsequently controls prosthesis. However, practical execution of this technology possesses some challenges like obtaining precise and desired signals, processing, and identifying the distinction between muscular activity and muscle fatigue (Park and Meek 1993). The kinematic and kinetic signals taken from several positions around the knee on amputated and sound limb of unilateral patients are used as soft signals for control of prosthesis. Continuity of works (Herr and Wilkenfeld 2003; Bar et al. 1983; Aeyels et al. 1992) in this direction has been able to replace a natural anatomic knee with a bionic one. This allows the amputee to achieve a suitable gait and human operation of it. Robotic systems are in operation with notions like CPGs, for producing joint tracking and harmonizing them to breed the various gait modes (Brambilla et al. 2006; Muthuswamy 2005; Billard and Ijspeert 2000). Currently, the cybernetic era of prostheses can apply bio-stimulated conceptions to get knee joint trajectory, walking modes, and overall performance in smooth and reliable way.

There have been various studies regarding control algorithm in prosthetic knee. There have been practical implementations of various machine learning techniques for automatic inception of control rules on human motions (Jonic et al. 1999) and exploration of inherent propulsion of human locomotion (Popovic et al. 2004). Most commonly used machine learning algorithms used in prosthetic knees include SVM and neural network-based control algorithm (ANN and CNN). There exists higher classification accuracy in SVM as it can be combined with other pattern classification methods to target different objectives (Labarrière et al. 2020). The ANN features significantly lower classification error than LDA ($p < 0.05$) (Woodward et al. 2016). CNN is often used to avoid manual feature selection and reported with accuracy above 89%. This has been reported that an adaptive algorithm performs significantly better than a non-adaptive algorithm and possesses an encouraging solution to achieve long-term locomotion mode classification (Liu et al. 2017). Kalanovic et al. (2000) proposes a feedback error learning (FEL) neural network approach for control structure of a powered prosthesis. This approach identifies the inverse dynamics of straight-forward single joint movements of an arbitrary trans-femoral prosthesis, which may be wont to track an arbitrary trajectory or a particular walking pattern. However, to achieve the convergence of neural network weights, learning rate must be adjusted, because it is extremely sensitive and no known method aside from trial and error which will guarantee the weights to converge to the simplest value. Another study (Herr and Wilkenfeld 2003) proposes a user-adaptive control for a variable-damping electronic knee. This approach utilizes data from sensors located on knee axis to adapt damping

Table 1 Summary of control strategies and machine learning techniques used in prosthetic knee control

Author	Control approach	Control modes	Gait control	Hardware level	Machine learning technique	Measured signals	Type
Joshi et al. (2010)	Echo control with radio frequency wireless communication	GLW	–	ATMEL microcontroller	Low computational algorithm	Mechanical	Experimental
Sup et al. (2008)	Impedance control	GLW	FSM	Variable impedance		Mechanical	Powered
Varol and Goldfarb (2007)	Real-time gait intent recognition approach	Standing; slow, normal and fast GLW	–	–	k-Nearest neighbor algorithm	Mechanical	Powered
Varol et al. (2008, 2009)	Supervisory control	Standing, sitting, GLW	FSM	Variable impedance	Expectation Maximization (EM) algorithm	Mechanical	Powered
Varol and Goldfarb (2007)	Decomposition-based control	GLW	FSM	Torque control	Decomposition algorithm	Mechanical	Powered
Grimes et al. (1977)	Step input position control	GLW	Position controller	Position feedback loop, Torque control	–	Mechanical	Active
Liu et al. (2014)	Finite State Impedance Control	GLW	FSM	Impedance controller	–	Mechanical	Active
Lambrecht and Kazerooni (2009)	Finite State Impedance Control	GLW, stairs and inclines	FSM	Servo controller, position valve control	–	Mechanical	Semi-active
Martinez and Herr (2009)	Finite State Impedance Control	GLW	FSM	Variable impedance	Generic algorithm	Mechanical	Active
Lawson et al. (2013)	Finite State-based Control	Stair ascent and descent	FSM	Variable impedance	Supervisory control algorithm	Mechanical	Powered
Huang et al. (2009)	EMG-based control combined with pattern recognition	GLW, obstacles, climbing and descending stairs, Contralateral and ipsilateral turning and standing	Gait pattern generators	Leave-one-out cross-validation	EMG PR algorithm	EMG. Mechanical	Powered
Wu et al. (2011)	EMG-based control	GLW	Gait pattern generators	Proportional EMG control	Active–reactive control algorithm	EMG, mechanical	Active

Table 1 (continued)

Author	Control approach	Control modes	Gait control	Hardware level	Machine learning technique	Measured signals	Type
Torrealba et al. (2012)	Adaptive CPG	Walking on a level treadmill	Continuous control approach	Amplitude controlled phase oscillators (ACPOs)	Statistics-based algorithm	Mechanical	Active
Geng et al. (2012)	CPG	GLW	Bipedal locomotion controller through non-linear dynamic theory	Adaptative Hopf oscillator	–	Mechanical	Active
Torrealba et al. (2010)	CPG	GLW	Knee Angle Generator	Amplitude Controlled Phase Oscillators, adaptive proportional controller	Accelerometer-based Events Detection Algorithm	Mechanical	Intelligent
Guo et al. (2010)	CPG and EMG control	GLW		MCU controller, non-linear Rayleigh oscillator	SVM algorithm	Mechanical, EMG	Active
Wen et al. (2020a)	RL-based control	Walking on a level treadmill	FSM	Impedance control	RL algorithm	Mechanical	Robotic
Jelacic (2019)	Sensor real-time control	Walking and ascending stairs	Position controller or knee angle tracker	Robust passivity-based controller	Proportional integral-Derivative algorithm	Mechanical	Active
Herr and wilkenfeld (2003)	User-adaptive control	GLW	FSM	User-adaptive controller	Adaptive algorithm	Mechanical	Active
Woodward et al. (2016)	Intent-recognition system using ANN	GLW, stairs ascent, stairs descent, and ramp descent	State-machine progression	Impedance control, Position feedback loop, Torque control	Scaled conjugate gradient learning algorithm	Mechanical	Powered
Sup et al. (2010)	Finite State Impedance Control	Up slope walking	FSM	Impedance control	–	Mechanical	Powered
Guo et al. (2006)	EMG Processed control using ANN	GLW, slope and stair	–	Identical EMG control multilayer threshold	Levenberg–Marquardt algorithm and	EMG	Active
Afzal et al. (2015)	EMG-based control	Non-weight-bearing movements	–	–	Fast Non-negative Matrix Factorization (FNMF) algorithm	EMG	Active
Ekkachai and Nilkhamhang (2016)	CPG and Neural Network Predictive Control	Walking on a level treadmill	Gait pattern generators	Torque control, PID controller	User-adaptive control algorithm	Mechanical	Semi-active

Table 1 (continued)

Author	Control approach	Control modes	Gait control	Hardware level	Machine learning technique	Measured signals	Type
Lawson et al. (2011)	User-adaptive control	Standing slopes	FSM	Impedance control, torque control	Inertial measurement unit (IMU) algorithm	Mechanical	Intelligent powered
Zhang et al. (2013)	Real-time user intent recognition control	GLW, stair ascent, stair descent, ramp ascent, ramp descent, sitting, and standing	Gait-phase detector and mode recognition	Threshold EMG control	Intent-recognition algorithm	EMG, mechanical	Powered
Dedic and Dindo (2011)	Adaptive control system	Slope walking or stairs climbing	Motor control recognition	Adaptive controller, torque control, microprocessor	Neural Networks, Support Vector Machines, Bayesian classifiers	Mechanical	Active
Dutta et al. (2011)	Adaptive and EMG processed control	GLW, walking up a ramp, and walking down a ramp	FSM	Threshold EMG control	Mode-specific adaptive Kalman filter algorithm	EMG, mechanical	Powered
Maqbool et al. (2015, 2016)	Sensor-based real-time control	GLW, ramp ascending and descending	Real-time gait event detection	Inertial measurement unit (IMU) comprising of accelerometer and gyroscope	Robust real-time gait event detection algorithm	Mechanical	–
Shaikh and Malhotra (2020)	Real-Time Feedback Control	GLW and staircase walking	Feedback from the stance detector	Inertial measurement units (IMU), gyroscope and a 3-axis accelerometer	Motion Fusion Algorithm	Mechanical	Active
Sup et al. (2009)	Finite-state-based impedance control, intent recognizer	Walking and standing	FSM	Impedance control	–	Mechanical	Powered
Wen et al. (2020b)	Approximate dynamic programming (ADP) learning control	Walking on a level treadmill	Knee Angle Generator and learner	ADP-tuner and controller	Online Reinforcement Learning	Mechanical	Robotic
Gorsic et al. (2014)	Sensory closed loop real-time feedback control	GLW	FSM	State transitions and joint trajectory generations	Rule-based phase detection algorithm	Mechanical	Robotic
Hargrove et al. (2013a; b)	Real-time EMG Processed control	Non-weight-bearing	FSM	Impedance controller, Torque control, pattern recognition system	Linear discriminant analysis (LDA)	Mechanical	Powered

Table 1 (continued)

Author	Control approach	Control modes	Gait control	Hardware level	Machine learning technique	Measured signals	Type
Shirsath and Dongare (2016)	EMG Processed control using ANN	GLW	Real-time gait event detection	Variable-impedance control, locomotor mode recognition	ANN algorithm	EMG, Mechanical	Semi-active
Aghasadeghi et al. (2013)	Impedance control	GLW	Kinematic joint trajectory	Impedance control, torque control	Impedance parameter learning algorithm	Mechanical	Semi- active
Du et al. (2013)	Adaptive pattern recognition Neural machine interface control	GLW, stair ascent, stair descent, ramp ascent and ramp descent		Feature Extraction and Pattern Recognition system	Support vector machine entropy-based adaptation and Learning From Testing Data (LIFT) adaptation algorithm	EMG, mechanical	Powered
Bhakta et al. (2020)	Impedance-based hierarchical control	GLW, ascending/descending slopes	FSM	Torque actuation, closed loop feedback control. Impedance-based control	User intent machine learning algorithm	Mechanical	Powered
Khademi et al. (2019)	User intent recognition control	Standing and level walking in treadmill	Multi-layer perceptron (MLP) classifier	Feature extraction, threshold-based control	SVM, biogeography-based optimization algorithm, gradient-based multi objective feature selection algorithm	Mechanical	–
Wen et al. (2017)	Adaptive control system	GLW	FSM	Finite state impedance control, dynamic walking simulator	Adaptive dynamic programming (ADP) control algorithms	Mechanical	Powered
Bai et al. (2015)	Smart system supporting volitional control	GLW	Volition-detection system controller	Threshold EEG control	Modified Laplacian reference algorithm	EEG	Powered
Chen et al. (2008)	Posture recognition control	Stair, sitting, standing and walking		Intelligent control by pattern recognition, physical feedback	SVM and NN-GA algorithm	EMG	Powered
Lenzi et al. (2017)	Active variable transmission (AVT)	GLW, reciprocal stair gait	–	Torque control, Closed-loop position control	–	Mechanical	Powered
Joshi et al. (2011)	Adaptive ANN control system	GLW	ANFIS for knee trajectories		Adaptive Neuro-Fuzzy Inference System algorithm	Mechanical	–

Table 1 (continued)

Author	Control approach	Control modes	Gait control	Hardware level	Machine learning technique	Measured signals	Type
Simon et al. (2014)	Finite State Impedance Control	GLW, ramp ascent/descent, and stair ascent/descent	FSM	Impedance control, torque control	–	Mechanical	Powered
Huang et al. (2011a)	Neuromuscular–mechanical fusion for neural control	GLW, stepping over an obstacle, stair ascent, descent, ramp ascent, descent		Locomotion-mode recognition	SVM algorithm	EMG, Mechanical	Powered
Fey et al. (2014)	Finite state impedance-based control	GLW, inclined surface	FSM	Impedance control, torque control	Joint impedance modulation algorithm	Mechanical	Active
Jongprasithporn et al. (2018)	Intent-recognition system using ANN	GLW, walking up and down stairs, regular sitting, upright standing and lying	Feed-Forward ANN with back-propagation learning	–	UCI Machine Learning Repository algorithm	Mechanical	Powered
Kalanovic et al. (2000)	Feedback-error learning neural network control	GLW	FSM	Feedback-error learning controller, Position feedback control, Torque control	–	Mechanical	Powered
Kadhim et al. (2020)	Adaptive Neuro-based Fuzzy control	GLW	Pattern recognition and adaptive control	ANFIS controller	Back-propagation learning algorithms	Mechanical	Active
Baby et al. (2020)	EMG-based control	GLW	Sensor inputs from the IMU and EMG	Locomotion-mode recognition, pattern recognition and knee angle and position detection	SVM, random forest algorithm	EMG	Powered
Huang et al. (2011b)	Radio frequency identification (RFID) system	GLW	Gait pattern classifier feedback control	Radio frequency identification (RFID) readers for positioning information	Decision tree, fast learning neural networks	Mechanical	Intelligent powered
Wu et al. (2021)	Impedance control	GLW	FSM	Impedance intrinsic controller	Reinforcement Learning algorithm	Mechanical	Robotic

FSM finite-state machine, *GLW* ground-level walk, *EMG* electromyography, *CPG* central pattern generator, *SVM* support vector machine, *ANN* artificial neural network, *RL* reinforcement learning values of knee for matching the amputee's gait. The results show that the proposed open-loop controller performs better to match with biological gait compared to the mechanical passive knee. A study combining the four-bar link mechanism that usually employed in passive knees with MR damper is presented in Xie et al. (2010). The modeling and control proposed are a parametric approach, and thus contains many parameters to be defined. The results showed that the inteligent control proposed during this study is ready to follow the gait tracking of the healthy side of amputee leg in spite of particular delay. MR damper has been widely utilized in various applications. In robotics field, the study investigated by Garcia et al. (2011) proposed a mixture of MR damper and series elastic actuation for locomotion control for all-terrain robot. There are two control schemes utilized in this study, i.e., direct joint force control employing a PID control to come up with current command to the amplifier module and a cascade controller within the amplifier module. The results show that the proposed combined actuator and control can achieve a natural looking motion and can also reduce 20% of power in braking knee mechanism.

A variable stiffness control as proposed by Wentink et al. (2013) has been investigated in a modeling study of prosthetic knees to revive knee buckling during stance. Rotational stiffness is controlled to forestall excessive knee flexion, which is vital to supply a traditional gait. Torque generation in stance phase around the knee ensures normal gait trajectory and avoids risk of falling in amputees. EMG-based modeling approaches have been investigated that used joint kinematics and EMG data as input to the model (Lloyd and Besier 2003; Kwon et al. 2012; Schauer 2017). Swing phase control structure as proposed by Ekkachai and Nilkhamhang (2016) consists of a neural network predictive control with particle swarm optimization, and also a non-parametric feed forward neural network swing phase model. It utilizes knee angle data and voltage commands as the input to the controller. The performance of this controller was measured by normalized root mean squared error with validated data from an experiment. The results show that this controller performs better than the user-adaptive control found in Herr and Wilkenfeld (2003). Moreover, huge differences in outcome parameters of these reviewed studies investigating similar control strategies and machine learning techniques did not allow a meta-analysis to be performed.

5 Conclusion

This literature review has focused on control strategies and machine learning techniques applied to knee prostheses. Advancements in electronics, fluid mechanics, and mechanical knowledge provide the real-time functioning of active or powered prosthesis to attain a natural gait. The control approaches cannot be generalized, and may vary depending on variation of characteristics of disabilities, available prosthetic devices, organization of executed control schemes, and necessity of prosthesis to identify the gait episode or the user's intent. Machine learning approach has been used to automatically optimize the high-dimension control parameters of the advanced knee prosthesis. Multiple algorithms have been proposed and used to control prosthetic knees for specific tasks and best suits the needs of amputees. The correct combination of control strategies and machine learning techniques will enable the improvement of prosthetic performance and enhance the quality of life of amputees. Future work on quantitative indicators of execution of the suggested algorithms, error measurements in joint trajectories, and functional outcome measure under realistic conditions are warranted with a comprehensive perspective to focus and resolve challenges of current prosthetic knees.

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