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Kinematic variables for upper limb rehabilitation robot and correlations with clinical scales: A review

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ABSTRACT

The paper presents a comprehensive review carried out to identify the kinematic variables used in upper body rehabilitation assisted by robotic devices to assess the motor impairment of stroke patients and investigates the correlation between the kinematic variables and the clinical scales. Twenty-nine kinematic variables have been studied from twenty-eight articles involving 738 subacute or chronic stroke patients. The movement of speed, distance, accuracy, peak speed, peak speed ratio and number of peak speed were found to be the most frequently used kinematic variables in the aforementioned studies. Seven out of twenty-eight included articles examined the correlations between the kinematic variables used with the clinical scales. Some kinematic variables seem to have a strong correlation with the clinical scales but most of the kinematic variables have a moderate or weak correlation value. The important kinematic variables for evaluating the motor performance during rehabilitation assisted by robotic devices have been discussed. A suitable selected set of kinematic variables and clinical scale can potentially enhance the correlation value, at the same time can predict the clinical score evaluated by physiotherapist during the rehabilitation program with a high degree of accuracy.

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1. INTRODUCTION

Nowadays, many types of upper limb robotic device or rehabilitators for stroke rehabilitation have been developed to assist physiotherapists during rehabilitation program. Assessing the motor function of stroke patients using clinical scales by physiotherapist is difficult due to the limitation of time and resources [1]. The systematic reviews on the effects of robotic rehabilitator with stroke patients have been increased in recent years [2-4]. These robotic rehabilitators provide precision measurement of patient's sensory motor performance which can positively influence the rehabilitation outcome [2]. In previous studies, kinematic variables evaluated by the robotic rehabilitators have been used as indicator for assessing patient's motor performance. Furthermore, kinematic evaluated by the robotic rehabilitator can be easily analyzed after each rehabilitation session compare to clinical outcome measures [1]. Many kinematic variables have been used in the robotic rehabilitation system. Some kinematic variables have different names in spite of having the same meaning. Even though the kinematic appropriateness to capture the intended changes has been analysed [1, 5], there is no general agreement on the best fit kinematic variables that proposed be used.

Kinematic variables used in the robotic assessment become more meaningful in the assessment process. This is because the analysis of kinematic parameter recorded during the assessment highlight the motor performance of the stroke patient. The correlations of the kinematic variables and the clinical scales in stroke rehabilitation using robotic devices have been studied by various researchers [6-10]. The conventional clinical scales such as Motor Assessment Scales (MAS), Modified Ashworth Scale (MoAS), Fugl Meyer Assessment (FMA) and others are extensively used to evaluate the motor performance of stroke patients. Even though these conventional clinical scales have been extensively used and are well-established, the correlation agreement between kinematic variables with these conventional clinical scales must be strengthened. Providing the credible and more quantitative evaluation methods during the rehabilitation process is the main purpose of this correlation value. Besides, the value of this correlation is important and can be used to select a suitable set of kinematic variables coupled with the appropriate clinical scales for evaluating the motor impairment in rehabilitation program [1].

This review paper focuses on the kinematic variables and the correlation with the clinical scales used in upper limb rehabilitation robotic system. The first objective of this study is to identify the kinematic variables used by robotic rehabilitator to evaluate the motor performance in stroke rehabilitation program. The second objective is to examine the correlation of the reviewed kinematic variables and clinical scales used in the related studies. The outcomes of this review paper can be used to recognize the suitable kinematic variables or parameters to be used in order to predict the clinical score evaluated by physiotherapist during the rehabilitation program.

2. RESEARCH METHOD

The method to carry out this review was divided into two stages including database research and identification of the correlation value between kinematic variables and clinical scale within the included articles. The first stage focuses on the finding of articles that involve upper limb robotic rehabilitation of stroke patients, where kinematic variables were used as a part of the performance evaluation. There are four search method; i) Find related articles, ii) Inclusion criteria: the studies must use robotic device, at least five stroke patients involved, and at least one kinematic variable used, iii) Removal of the duplicated and review articles, iv) Filtering and searching the list of referenced in selected articles for other related articles. The second stage focuses on tabulation of the identified kinematic variables that were used in stroke rehabilitation program using robotic device and its correlation with clinical scales. Full article content was readable to identify each correlation value of included kinematic variables. Besides, the correlation values between the kinematic variables and clinical scales used in the relevant studies also tabulated for comparison purposes. The process follows by analyse the correlation values between kinematic variables and clinical scales. The classification of the correlation value was elucidated 0.0–0.3 as weak correlation, 0.3–0.7 as moderate correlation and 0.7–1.0 as strong correlation [1, 11].

3. RESULTS AND DISCUSSION

The literature search resulted in 112 (IEEE Xplore), 154 (Scopus) and 83 (PubMed) articles. As the result, 28 studies published from 2012 to 2018 (involving 738 stroke patients) satisfying the inclusion criteria were included in this systematic review through the literature search method. Based from the included articles, 29 kinematic variables were identified and the equivalent definition has been classified. Same kinematics variables termed differently in various lituratures were classified together in this review study as presented in Table 1.

There are a variety of robotic devices that have been developed and used to help physiotherapy in stroke rehabilitation process [1, 35]. In this study, 13 upper limb rehabilitation robots or robotic devices were managed to report the kinematic variables related to the assessment of motor performance during rehabilitation process as shown in Table 2. Based on the results, the most frequently used kinematic variable in upper limb rehabilitation for stroke patients are: MSpeed, MDis, MAcc, PSR, PS and NPS. Regarding to the included articles in this study, MSpeed is the most frequently used kinematic variable for evaluating the motor function of upper limb diasbility. Thus, the MSpeed need to be considered as stable kinematic variables for evaluating the motor function of the stroke patients. The analysis of kinematic variables combined with the clinical scales used in rehabilitation assisted by robotic devices becoming the advantages to support and predict the clinical scales score. Based on the included articles, only 16 kinematic variables stated the correlation value with the clinical scales. There are 9 types of clinical scales included in this review. Table 3 presents the correlation values between the kinematic variables and the clinical scales used in the related studies.

Table 1. Properties of the used kinematic measures

Kinematic variables	Definition
Acceleration Metric (AM)	The allocation of the acceleration that used in the planar motion [12, 13].
Displacement (Dis)	The capability of patients to make a movement of the arm opposite to the resistance in each of 8 directions of the compass [14].
Efficiency Index (EffInd)	The formula of Normalized path length (nPL)= $(\sum_{i=1}^{n}\|dPi\|)/PLt$ has been used to calculate the movement efficiency. The PLt is the theoretical path length while dPi is the distance between two points of the patient's path [15].
Force Parameters (ForceP)	The Pretest, Retention Test and Post -Test use the Pull, Push and Grip strengths of the patients for assessing the force [16, 17].
Hold Deviation (HD)	The average of the deviation distance when try to hold the arm opposite to resistance across the 8 directions is called the hold deviation [14].
Initial Distance Ratio (IDR)	The ratio of the distance of hand traveled during the patients' initial movement to the distance the hand traveled between onset and offset movement [6, 18].
Jerk Metric (JM)	Defined as the average rate of change of a movement acceleration, calculated by (-ve) mean jerk magnitude divided by the peak speed. Taking the (-ve) mean jerk makes increment of the jerk metric in line with increment of the smoothness [7, 12, 19, 20].
Movement duration (MDur)	The total time when the movement travelled from the onset to offset [6, 21].
Movement onset time (MOT)	Defined as the situation when the patient starts to move the upper limb robot toward the target without hesitation. Calculated when movement speed > 10% peak speed, by selecting the time [22].
Movement accuracy (MAcc)	Defined as the accuracy ratio between the entire distance travelled by the patients from movement onset to offset and task distance [6, 7, 14, 17, 18, 23-26].
Movement distance (MDis)	Defined as the entire distance travelled by the patients' hand between the movement onset and the movement offset [6, 7, 12-14, 17, 18, 27, 28].
Mean Position (MeanP)	Mean position data in pronation or supination, flexion or extension and abduction or adduction movements of hand wrist in direction North, East, South and West toward [29].
Movement smoothness (MSmooth)	The jerk metric and number of peak speed kinematic variables were analysed to calculate the smoothness of the movements [19, 20].
Movement Speed (MSpeed)	Total displacement divided by total movement of duration [6, 7, 12, 13, 15, 20, 21, 23, 24, 27-30]. "Movement time"- the total time elapsed to reach within a centimeter from the target [31].
No Movement End (NME)	The number of tests that stopped at target destination was detected, for instance the patients did not stabilize or reach the peripheral target [6].
Number of Peaks Speed (NPS)	"Peaks metric" used as (-ve) number of peaks to makes increment of the peaks metric in line with increment of the smoothness [6, 23, 15, 20, 21, 28]. The distance travelled and the number of data has normalized the number of peaks in the velocity profile [25, 26, 32].
No Reaction Time (NRT)	The number of tests where the movement of the patients' hand to the target position could not be detected [6].
Percentile Coverage Metric (PCM)	Calculate the 50th percentile contour of 2D velocity first, and then calculate the coverage (m^2/s^2) inside the boundary developed by this contour [33].
Peak Speed (PS)	The highest hand speed during the test (Peak speed or Max speed or Peak velocity) [6, 7, 17, 18, 21, 23].
Peak Speed Ratio (PSR)	The metric of movement smoothness can be evaluated by dividing the mean speed with the peak speed [7, 14, 15, 21, 23, 24, 28].
Time to Peak Velocity (TPV)	The TPV defined as the percentage of the time to reach the peak velocity of the patients' hand movement [26]. The difference between the time where peak velocity has been reached and the time where velocity firstly exceeds five percent of peak velocity can determine the TPV [34].
Root-Mean Square Error (RMSE)	Linear regression has been used for RMSE to assess the deviation path of straight line located between the starting posision and end position of the robot's handle [34].
Robot Power (RP)	Robot power was calculated using formula: Force multiply with Velocity. The RP value will be near to zero if the stroke patients performing the required movement without any assistance [8].
Reaction Time (RT)	The time between the onset of movement and the illumination of the peripheral target [6, 18].
Slottime (SlotT)	Defined as the time allocated to the patient to accomplish the assessment task. Two seconds allowed as the starting time. When the patient moves faster, the allocated time is gradually decreased to one second. This kinematic variables related with velocity [8].
Stiffness (Stif)	Defined as force or displacement kinematic that used as a side guidance. When the stroke patients improved at aiming, the guidance is reduced for challenging the patient to make the better movements [8].
Straightness (Str)	Calculated by dividing the amplitude with the path length travelled by the stroke patients [7].
Submovement (SubMov)	Submovement consists of two components which were the "starting" impulse and the "current" control. The "current" control consisted of a sequence of excellent adjustments added to the "starting" impulse as the hand come nearer the target [21].
Task Completion Time (TCT)	The time needed to finish each assessment task [17, 18, 25].

Based on the tabulated results, the discussions are divided into three main points. The first point focuses the important kinematic variables for reaching movement since reaching is the main hand function in rehabilitation. In upper limb robotic rehabilitation, there are several basic movements for assessing motor performance of stroke patients which are planar reaching movement, draw square and draw circle shapes.

Table 2. Kinematic variables used in robotic assisted upper limb rehabilitation studies

Robotic device	Reference	Type of patients	N	Most frequently used kinematic variable						Others
				MSpeed	MDis	MAcc	PSR	PS	nPS	
MIT-MANUS (InMotion2 and InMotion3)	Colombo *et al.*, 2017 [28]	S/C	30	*	*		*		*	
	Duret *et al.*, 2016 [24]	S	38	*		*	*			
	Panarese *et al.*, 2016 [36]	S/C	12	*		*				
	Massie *et al.*, 2016 [31]	C	22	*						
	Duret *et al.*, 2015 [8]	S	25							Stif, SlotT, RP
	Yoo *et al.*, 2015 [14]	S/C	15		*	*	*			Ind, HD, Dis
	Mazzoleni *et al.*, 2015 [29]	S	12	*						MeanP
	Mazzoleni *et al.*, 2014 [20]	S/C	24	*					*	JM, MSmooth
	Mazzoleni *et al.*, 2013 [22]	S/C	50	*					*	AM, MOT
	Mazzoleni *et al.*, 2012 [27]	C	11	*	*					
	Dipietro *et al.*, 2012 [21]	S/C	158	*			*	*	*	SubMov, JM, MDur
Armeo Spring	Luca *et al.*, 2017 [25]	C	16			*				TCT, MDur
	Longhi *et al.*, 2016 [23]	S/C	44	*		*	*	*	*	JM
	Grimm *et al.*, 2016 [17]	C	5		*	*		*		ForceP, TCT
Planar robot	Laczko *et al.*, 2017 [12]	C	19	*	*					AM, JM
	Huang *et al.*, 2016 [13]	C	10	*	*					AM
	Wright *et al.*, 2015 [33]	C	12							PCM
MEMOS	Colombo *et al.*, 2017 [28]	S/C	23	*	*		*		*	
	Colombo *et al.*, 2014 [15]	S/C	31	*	*		*		*	EffInd,
KINARM	Otaka *et al.*, 2015 [6]	C	56	*	*	*		*	*	RT, IDR, NRT, NME, MDur
PUPArm	Lledo *et al.*, 2016 [18]	S	9		*	*		*		IDR, RT, TCT
BdF	Colombo *et al.*, 2017 [28]	S/C	34	*	*		*		*	
iRest	Rahman *et al.*, 2015 [26]	S/C	14			*		*	*	RT, TPV, MDur
RUPERT	Huang *et al.*, 2016 [19]	N/A	6							JM, MSmooth
H-Man	Hussain *et al.*, 2016 [34]	C	12							TPV, RMSE
WAM	Cho *et al.*, 2015 [30]	C	10	*						
UL-EXO7	Simkins *et al.*, 2016 [16]	C	15		*					ForceP
ReaPLAN	Gilliaux *et al.*, 2014 [7]	N/A	25	*	*	*	*	*		Str, JM

Note: S: Sub-acute patients; C: Chronic patients; N: Number of patients; *: Used in studies; N/A: Not Available

These tasks movement requires the stroke patients to move their affected wrist or hand. In recent study, the patients need to perform four types of movement task which were (Circle and Free Amplitude tasks) as the rhythmic movements and (Square and Target tasks) as the discrete movements [7]. For the Free Amplitude task, the MDis, MSpeed, Str, PS and two smoothness metrics (the MSpeed and JM) were calculated. For the Target task, the MAcc has replaced the MDis. For the Circle and Square tasks, the MSpeed, PS, PSR, JM and MAcc indices were calculated [7]. The other study required the patients to perform three assessment modules which are Draw capital I task for isolated movement, Draw Diamond and Draw Circle task for combined movements of hand reaching and hand manipulation (pronation/supination) [32]. These assessment module used to compute the MAcc, MDur, PS, nPS, RT, and TPV [32]. Hence, the MAcc and PS should be considered as the important kinematics for evaluating the motor performance of patiets' upper limb when it involves reaching movement.

The second point identifies the recommended kinematic variables to evaluate the motor function. Most of the included articles assessing the motor performance using the PS, nPS, PSR and MAcc. The PS, nPS, PSR were computed from the velocity profile has been used to calculate the smoothness of the patients' hand movement during rehabilitation process [20, 32]. From Table 3, the PS has a week correlation with the FMA [6, 7], but it has a moderate correlation with the MAS clinical scale [32]. The nPS showed a moderate correlation with the FMA, MAS, SIAS-KM, WMFT-FAS and the WMFT-time scales [6, 23, 32]. In recent study [32], the nPS was funtioned to determine the smoothness of the movement during the patients performing their rehabilitation program using the robotic device. The values of nPS kinematic used in three types of assessment task which are Capital I task, Diamond task, and Circle task [32]. Since the motor recovery of the patient also reflected by the accuracy of the movement, most clinical scales have a strong correlation value with the MAcc [24, 32]. In addition, the MDur is also considered as the important kinematic variable that used to calculate the time taken for the patients execute the movement from onset to offset, which the time taken is expected to reduce when the patients performing the rehabilitation task [6, 21]. Based on the correlation between the kinematic variables and the clinical scales, the MDur, MAcc, MSpeed, nPS, PS can be classified as the recommended and important kinematic variables to evaluate the motor function during the rehabilitation process that were assisted by robotic devices or rehabilitator.

Table 3. Correlations between kinematic variables and clinical scales

Kinematic Variables	Clinical scales								
	FMA	MSS	MoAS	MAS	MI	BBT	SIAS-KM	WMFT-FAS	WMFT-time
AM	-0.217[a] [22] 0.117[b] [22]				-0.2[a] [22] -0.2[b] [22]				
IDR	0.58 [6]		-0.47 [6]				0.43 [6]	0.64 [6]	-0.47 [6]
JM	-0.31[c] [7] -0.30[d] [7] -0.13[e] [7] -0.41[f] [7]					-0.38[c] [7] -0.24[d] [7] 0.03[e] [7] -0.23[f] [7]			
MDur	-0.52 [6]		0.44 [6]	-0.31[i] [32] -0.32[j] [32] -0.16[f] [32]			-0.45 [6]	-0.60 [6]	0.40 [6]
MAcc	-0.60 [6] -0.20[d] [7] -0.14[e] [7] -0.15[f] [7] -0.79[g] [24] -0.65[h] [24]	-0.79[g] [24] -0.49[h] [24]	0.46 [6]	0.76[i] [32] 0.34[j] [32] 0.77[k] [32]		-0.51[d] [7] -0.41[e] [7] -0.13[f] [7]	-0.42 [6]	-0.57 [6] -0.36 [23]	0.42 [6] 0.44 [23]
MDis	0.22[c] [7]					0.30[c] [7]			
MSpeed	0.57[(ISR)] [6] -0.40[(MMS)] [6] -0.24[(PHS)] [6] -0.16[c] [7] -0.38[d] [7] -0.01[e] [7] -0.28[f] [7] 0.73[g] [24] -0.04[a] [22] 0.069[b] [22]	0.73[g] [24]	-0.47[(ISR)] [6] 0.36[(MMS)] [6] 0.03[(PHS)] [6]		-0.1[a] [22] -0.2[b] [22]	-0.30[c] [7] -0.44[d] [7] -0.06[e] [7] 0.05[f] [7]	0.42[(ISR)] [6] -0.28[(MMS)] [6] -0.04[(PHS)] [6]	0.62[(ISR)] [6] - 0.24[(MMS)] [6] -0.01[(PHS)] [6] 0.31 [23]	0.44[(ISR)] [6] 0.08[(MMS)] [6] 0.01[(PHS)] [6] -0.26 [23]
NME	-0.58 [6]		0.37 [6]				-0.49 [6]	-0.58 [6]	0.4 [6]
NPS	-0.58 [6] 0.028[a] [22] -0.016[b] [22]		0.47 [6]	-0.59[i] [32] -0.38[j] [32] -0.19[f] [32]	0.04[a] [22] 0.31[b] [22]		-0.45 [6]	-0.59 [6] -0.5 [23]	0.4 [6] 0.56 [23]
NRT	-0.54 [6]		0.27 [6]				-0.46 [6]	-0.52 [6]	0.37 [6]
PS	-0.06 [6] -0.2[c] [7] -0.47[d] [7] -0.14[e] [7] -0.31[f] [7]		-0.08 [6]	0.65[i] [32] 0.85[j] [32] 0.52[f] [32]		-0.34[c] [7] -0.52[d] [7] -0.31[e] [7] -0.04[f] [7]	-0.09 [6]	0.08 [6] 0.15 [23]	-0.14 [6] -0.1 [23]
PSR	-0.208[a] [22] 0.123[b] [22] 0.02[c] [7] 0.21[d] [7] 0.12[e] [7] -0.11[f] [7] 0.75[g] [24]	0.72[g] [24]			-0.1[a] [22] -0.3[b] [22]	0.04[c] [7] 0.13[d] [7] 0.25[e] [7] 0.32[f] [7]		0.45 [23]	-0.44 [23]
TPV				-0.18[i] [32] 0.22[j] [32] 0.25[f] [32]					
RT	-0.32 [6]		0.15 [6]	0.01[i] [32] -0.46[j] [32] -0.19[f] [32]			-0.28 [6]	-0.2 [6]	0.19 [6]
Stif	0.4 [8]								
Str	0.28[c] [7] 0.33[d] [7]					0.28[c] [7] 0.41[d] [7]			

[a] : Subacute patient; [b] : Chronic patient; [c] : Free amplitude task; [d] : Target task; [e] : Square task; [f] : Circle task; [g] : Baseline correlations; [h] : Correlation between changes in clinical scales; [i] : Capital I task; [j] : Diamond task; ISR: Initial speed ratio [6]; MMS: Min-max speed [6]; PHS: Postural hand speed [6]; MSS: Motor Status Score; MP: Motor Power; MI: Motricity Index; BBT: Box and Block Test; SIAS-KM: Stroke Impairment Assessment Set-Knee Mouth Test; WMFT-FAS: Wolf Motor Function Test-Functional Ability Scale; WMFT-time: Wolf Motor Function Test-time to perform the task.

The third point focuses on comparison method of the correlation value. Good correlation values can be found when the kinematic variables showed a strong correlation with the clinical scale. However, only non-significant or weak correlation with the same clinical scale was identified in the included studies. For example, the FMA showed a strong correlation with the MSpeed (r=0.73) [24] in contrast with other study, the FMA showed a weak correlation with the MSpeed (r=0.069) [22]. Furthermore, the TPV have a positive correlation value with MAS scale in a circle task (r=0.25). Nevertheless, when the patients did performed the capital I task, this correlation has changed to negative values (r=-0.18) [32]. The differences of the patient's characteristics, types of assessment task and types of upper limb rehabilitation robot used makes the comparison process of correlation value become difficult. Thus, a good comparative method is required to standardize the type of kinematic variables, movement task and robotic assessment module used in the rehabilitation robot system.

The recommendation for selecting the proper outcome measures for evaluating the upper limb motor performance in robotic rehabilitation have been published [37]. Nevertheless, no guidance for selecting the suitable kinematic variables for the assessment process has been suggested. With regard to the important role of assessing motor function in the rehabilitation of the upper limb, kinematic variables should be considered in relation to the clinical scale. The authors suggested for use at least three kinematic variables or parameters to assess the upper limb motor performance in robotic rehabilitation program. Hence, the suitable combination between kinematic variables and clinical scale will assist the physiotherapist to assess the stroke patient's upper limb using robotic devices.

4. CONCLUSION

This review paper shows the various of kinematic variables were used in recent studies to assess the upper limb motor performance of stroke patients in rehabilitation program. The suitable kinematic variables to evaluate the motor function by robotic rehabilitator have been discussed. The MDur, MAcc, MSpeed, nPS, PS can be classified as the suitable kinematic variables to evaluate the motor function during the rehabilitation process. In addition, most of the correlation values have a weak and moderate correlation between the kinematic variables and the related clinical scales. As the outcomes of this review, the selection of the kinematic variables should be depended on the upper limb movement task used in the robotic system. Thus, a suitable combination of kinematic variables and clinical scale plays an important role in improving the correlation values, at the same time can predict the clinical score evaluated by physiotherapist during the rehabilitation program.

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