



Original Article

## Accuracy of wrist-worn heart rate monitors during physical therapy sessions among hemiparetic inpatients with stroke

MASAKI KOBAYASHI, RPT, PhD<sup>1)\*</sup>, TOMOYUKI SHINOHARA, RPT, PhD<sup>2)</sup>,  
SHIGERU USUDA, RPT, PhD<sup>3)</sup>

<sup>1)</sup> Geriatrics Research Institute and Hospital: 3-26-8 Ootomo-Machi, Maebashi 371-0847, Japan

<sup>2)</sup> Takasaki University of Health and Welfare, Japan

<sup>3)</sup> Gunma University Graduate School of Health Sciences, Japan

**Abstract.** [Purpose] We aimed to examine the accuracy of heart rate monitors worn on the wrist by patients with stroke. The wrist worn heart rate monitor could improve the quality of rehabilitation by monitoring exercise intensity during physical therapy. [Participants and Methods] Thirty inpatients with subacute hemiparetic stroke wore heart rate monitors on both (non-paretic and paretic) wrists, as well as a chest heart rate monitor. We recorded the heart rate values measured at the wrist and chest every minute during physical therapy sessions. The wrist monitors were an optical heart rate measurement device based on photoplethysmography, and the chest monitor was a traditional chest device based on electrocardiography. The relative and absolute reliabilities between the heart rate measurements from the wrist and chest monitors were calculated. [Results] The intraclass correlation coefficients for model 2.1 ranged from 0.75 to 0.79. Bland-Altman analysis revealed a very slight fixed bias; however, no significant proportional bias was observed. For the non-paretic and paretic sides, the lower and upper limits of agreement ranged from -21.8 to 23.8 beats/min and from -20.8 to 21.6 beats/min, and the mean absolute percentage errors were 6.7% and 5.9%, respectively. The Cohen's d value was small. [Conclusion] The relative reliability of the wrist heart rate monitors was substantial. The absolute reliability as bias in wrist heart rate and chest heart rate was small, but heart rates estimated from wrist monitors were not particularly accurate.

**Key words:** Exercise intensity, Reliability, Wearable device

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### INTRODUCTION

Aerobic exercise and moderate-to-vigorous activity for patients with stroke are strongly recommended to improve motor function and physical fitness<sup>1-3)</sup>. Experimental animal studies have shown that early aerobic exercise reduces lesion volume, oxidative damage, inflammation and cell death, and promotes neurogenesis and angiogenesis<sup>4)</sup>. Neurotrophins such as brain-derived neurotrophic factor, insulin-like growth factor-I and nerve growth factor are secreted during aerobic exercise and promote neuroplasticity and recovery following stroke<sup>5, 6)</sup>. Human studies have shown that aerobic exercise improves aerobic fitness, functional performance, cognitive function and quality of life<sup>7-11)</sup>. In addition, exercise combined with cardiorespiratory training and muscle-strengthening effects tend to reduce mortality in patients with stroke, although the odds ratio is large<sup>12)</sup>. Aerobic exercise thus appears important for patients with stroke.

Exercise intensity can be estimated using heart rates (HRs), rating of perceived exertion (RPE) and the Talk test<sup>13)</sup>. However, RPE and the Talk test can vary in their ability to estimate exercise intensity. RPE and the Talk test are subjective

\*Corresponding author. Masaki Kobayashi (E-mail: m11711005@gunma-u.ac.jp)

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methods to estimate exercise intensity. In addition, some patients with stroke have cognitive disabilities that could affect subjective perceptions of exercise intensity. However, HR is an objective marker for estimating exercise intensity and is unaffected by the cognitive condition of the patient. In the management of exercise intensity, exercise tolerance test by objective means is the best way to set aerobic exercise. HR thus remains the preferred means of monitoring and consequently prescribing exercise intensity<sup>14</sup>). Measuring HR is thus useful for monitoring aerobic exercise intensity.

The current gold standard for monitoring HR is electrocardiography (ECG), in which electrodes are placed on various sites of the upper body to measure electrical signals produced by the heart. However, ECG is expensive and electrical leads placed on the chest are attached to a telemeter and can thus impede physical therapy, which comprises various exercises. HR-monitoring devices should ideally be simple and lightweight. Optical blood flow sensing by photoplethysmography (PPG) is a popular optical means of monitoring HR by detecting changes in blood volume<sup>15</sup>) and devices can be conveniently worn on the upper arm or wrist.

Heart rate monitors worn on the wrist by healthy young adults are accurate and offer a valid means of monitoring HR at rest or while walking or running<sup>16–20</sup>). However, ageing is one factor associated with increased arterial stiffness, leading to changes in peripheral pulses propagation. In young adults, the characteristics of peripheral pulses in PPG are a steep rise and early peak<sup>21, 22</sup>). In elderly adults, the peripheral pulse wave in PPG shows a blunted slope and the systolic rise is more gradual<sup>21, 22</sup>). These characteristics of aging would affect the accuracy of HR measurements at the wrist, because HR measurements from the wrist are determined from the steep pulse intervals. In addition, arterial stiffness is higher in patients with stroke than in people without stroke<sup>23</sup>).

Patients with stroke showed reduced blood flow in the paretic lower limb<sup>24–26</sup>). In addition, vasomotor dysfunction was observed by flowmetry in patients with stroke<sup>27, 28</sup>). These responses indicate that HR measurement at the wrist using PPG may not be accurate. On the other hand, patients swing their arms irregularly and reach in various directions during exercise, and this can result in HR monitors worn on the wrist delivering variable results during physical therapy, because PPG signals are very susceptible by motion artifacts<sup>29</sup>). Comparing HR based on ECG, as the gold standard for monitoring HR, with HR measured at the wrist (wrist HR; WHR) based on PPG is important to investigate accuracy of HR monitors worn on the wrist.

The present study aimed to determine the accuracy of WHR monitors among patients with stroke. We postulated that WHR monitors should be reliable enough to monitor HR in such patients. If patients with stroke can wear wrist devices during physical therapy, aerobic exercise would be easier to manage, promoting physical and cognitive functions and overall health.

## PARTICIPANTS AND METHODS

Inpatients with subacute hemiparetic stroke at hospital were recruited between April and September 2018. Patients were usually treated with acute care for  $\geq 2$  weeks in an acute stroke unit until physical condition was stable. Inclusion criteria comprised hemiparetic stroke regardless of severity of paralysis and walking independence levels, no exercise restriction due to medical condition and ability to perform exercise during physical therapy. All participants were undertaking a 40- to 80-min physical therapy program that comprised exercises for range of motion, muscle strength, postural balance, transferring, and walking. Exclusion criteria comprised bilateral hemiparesis or inability to understand the study protocol or instructions provided by physical therapists. Thirty-two participants were initially recruited to this study. One patient was excluded due to an inability to follow instructions provided by a physical therapist and another dropped out after the chest HR monitor caused an adverse reaction of itch on the chest. Data from 30 participants were thus analyzed. Mean (standard deviation; SD) age of participants was 69.7 (11.3) years, 11 and 19 patients had right and left paralysis, respectively, and 13, 5 and 12 patients had assisted, supervised and independent gait, respectively. Four patients had a history of heart disease, in the form of atrial fibrillation (AF;  $n=2$ ), angina ( $n=1$ ) and myocardial infarction ( $n=1$ ) (Table 1).

This cross-sectional study was undertaken at a hospital in Gunma, Japan. All patients wore WHR monitors on the non-paretic and paretic wrists and a chest HR (CHR) monitor. WHR and CHR were measured during physical therapy sessions three times within 1 week. Sample size was not calculated. Strengthening the Reporting of Observational studies in Epidemiology (STROBE) guidelines were followed to standardize the present study<sup>30</sup>).

We used Polar A370 WHR monitors (Polar Electro, Kempele, Finland) and Polar H10 CHR monitors (Polar Electro, Kempele, Finland), connected to an Actigraph-wGT3X-BT (Manufacturing Technology, Pensacola, United States) to monitor physical activity<sup>31</sup>). The Polar A370 optically senses blood flow and provides HR based on perfusion in wrist blood vessels using PPG. The Polar H10 is ECG-based and has been used in many studies with accuracy comparable to that of ECG<sup>18, 32–34</sup>). CHR was used as the measurement criterion. Sampling frequency was 1 Hz for both the Polar H10 and Polar A370. These devices provided time-stamped HR data. For our analyses, we extracted values from the 3 devices every minute, then time-matched all non-zero HR data from the Polar H10 and Polar A370.

We analyzed age, height, body weight, body mass index, type of stroke, history of heart disease, Brunstrom Recovery Stage (BRS), gait independence and modified Rankin Scale (mRS) scores to define the characteristics of the participants. The BRS was used to assess paretic severity in upper and lower extremities and fingers. Scores range from 1 (flaccidity and no limb movement on the affected side) to 6 (near-normal to normal movement and coordination)<sup>35</sup>). Higher scores represent better motor function. Gait was assessed as “assisted”, “supervised” or “independent” during physical therapy sessions. The

**Table 1.** Characteristics of 30 participants

	Mean $\pm$ SD	n
Age (years)	69.7 $\pm$ 11.3	
Male/Female		17/13
Height (m)	1.60 $\pm$ 0.09	
Weight (kg)	55.8 $\pm$ 11.9	
Body mass index (kg/m <sup>2</sup> )	21.7 $\pm$ 3.7	
Ischemic/hemorrhagic stroke		15/15
Left/right hemiparesis		19/11
Brunstrom Recovery Stage, 1/2/3/4/5/6		
Upper extremity		2/7/2/3/7/9
Finger		4/6/1/0/8/11
Lower extremity		0/7/2/3/5/13
Gait ability (assisted/supervised/independent)		13/5/12
mRS, 0/1/2/3/4/5/6		0/3/6/6/14/1
History of heart disease, angina/myocardial infarction/atrial fibrillation		1/1/2

mRS: modified Rankin scale; SD: standard deviation.

mRS assesses the severity of post-stroke disabilities based on the degree of disability or independence in activities of daily living, with scores ranging from 0 (asymptomatic, independent) to 5 (severely disabled, requiring constant nursing care)<sup>36</sup>.

Data were statistically analyzed using R version 3.6.1 software (R Foundation for Statistical Computing, Vienna, Austria). An HR dataset was excluded when CHR data were missing. To estimate relative reliability, we used intraclass correlation coefficients (ICCs) for model 2,1 with 95% confidence intervals (95% CIs) between WHR and CHR, using the psych package<sup>37</sup>. ICCs were interpreted as: 0.0–0.2, slight; 0.21–0.40, fair; 0.41–0.60, moderate; 0.61–0.80, substantial; and 0.81–1.0, excellent<sup>38</sup>. To estimate absolute reliability, we used the mean absolute percentage error (MAPE), mixed-model Bland-Altman plots, and Cohen's d. MAPE was calculated to gauge general measurement errors of WHR and CHR (MAPE=absolute error/criterion  $\times$  100). We considered a MAPE <10% as indicative of accurate results<sup>39</sup>. Mixed-model Bland-Altman plots and limits of agreement (LOA) were constructed for WHR and CHR, including participant as a random effect, using the nlme package<sup>40–42</sup>. LOA were formulated as mean  $\pm$  1.96 SD. To investigate systematic bias, fixed bias was calculated from the LOA and 95%CI of the difference ( $\Delta$ ) between WHR and CHR. On the other hand, proportional bias was analyzed as Pearson's correlations with 95%CI between the difference and mean of WHR and CHR. Cohen's d were calculated for differences among non-paretic WHR, paretic WHR and CHR, using the effsize package<sup>43, 44</sup>. The level of significance was set at 0.05.

The institutional review boards at the Geriatrics Research Institute and hospital approved this study (approval no. 60) and all participants provided written informed consent to participate.

## RESULTS

The WHR and CHR amassed a total of 5,129 data points, from which 69 missing data points were excluded. We finally analyzed 5,060 data points. Mean differences (SD; 95%CI) between non-paretic or paretic WHR and CHR were 1.0 (11.6; 0.7, 1.3) beats/min and 0.4 (10.8; 0.1, 0.7) beats/min, respectively (Table 2). Cohen's d between WHR and CHR were 0.09 on the non-paretic side and 0.09 on the paretic side. Cohen's d between non-paretic and paretic sides was 0.06.

Bland-Altman plots showed the error distribution (Figs. 1, 2). On non-paretic and paretic sides, lower and upper LOA in mixed models were -21.8 beats/min and 23.8 beats/min and -20.8 beats/min and 21.6 beats/min, respectively.

Table 3 shows that the ICC (2.1; 95%CI) between WHR and CHR were 0.75 (0.74, 0.76) ( $p < 0.05$ ) and 0.79 (0.78, 0.80) ( $p < 0.05$ ) on the non-paretic and paretic sides, respectively.

## DISCUSSION

We investigated the accuracy of WHR monitors that used PPG to continually measure HR during physical therapy sessions. Relative reliability of WHR compared to CHR was substantial by ICC. Very slight fixed bias was revealed, but no significant proportional bias was evident from Bland-Altman plots. LOAs on non-paretic and paretic sides ranged widely. MAPEs were small for both non-paretic and paretic sides.

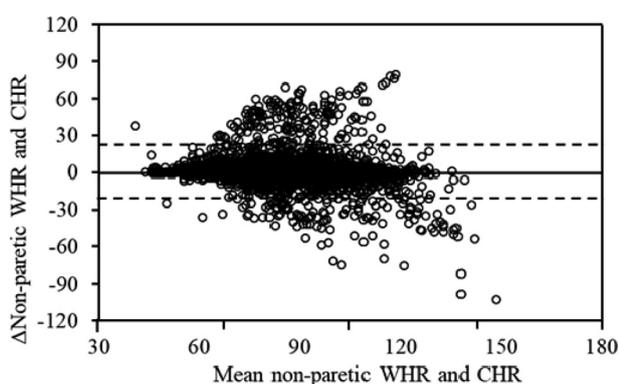
In terms of relative reliability, the ICC of WHR and CHR was substantial. Correlations between WHR and CHR were close for walking, but moderate for other activities<sup>18, 45</sup>. The change in vascular volume was larger at peripheral sites such as the wrist and finger when motion artifacts occurred, which could cause a large effect on the volume of distributed blood<sup>46</sup>.

**Table 2.** Comparison of chest and wrist HR (n=5,060)

	Mean	SD	Min	Max	95%CI	
					Lower	Upper
CHR (beats/min)	83.3	17.1	22.0	200.0		
Non-paretic WHR (beats/min)	84.3	15.8	38.0	158.0		
Paretic WHR (beats/min)	83.7	16.2	44.0	157.0		
Difference between non-paretic WHR and CHR (beats/min)	1.0	11.6	-103.0	79.0	0.7	1.3
Difference between paretic WHR and CHR (beats/min)	0.4	10.8	-98.0	76.0	0.1	0.7
Mean non-paretic WHR and CHR (beats/min)	83.8	15.4	41.0	148.5		
Mean paretic WHR and CHR (beats/min)	83.5	15.7	41.5	152.0		

Mean MAPE (SD) on non-paretic and paretic sides were 6.7 (6.7) % and 5.9 (4.1) %, respectively. Cohen's d between WHR and CHR were 0.09 for both non-paretic and paretic sides. Cohen's d between non-paretic and paretic sides was 0.06.

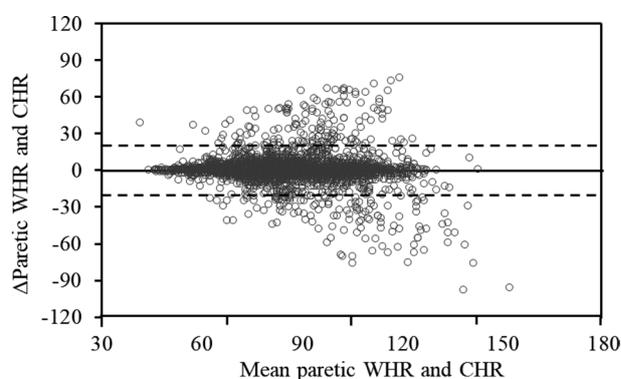
CHR: chest heart rate; CI: confidence interval; MAPE: mean absolute percentage error; SD: standard deviation; WHR: wrist heart rate.



**Fig. 1.** Bland-Altman plots of WHR and CHR on the non-paretic side.

Solid line indicates mean  $\Delta$ WHR and CHR. Dashed lines represent the upper and lower limits of agreement (LOA) for WHR and CHR. Lower and upper LOA were -21.8 beats/min and 23.8 beats/min, respectively. Pearson's correlation coefficient [95%CI] for mean and difference ( $\Delta$ ) between WHR and CHR was -0.11 [-0.14, -0.08] ( $p < 0.05$ ).

CHR: chest heart rate;  $\Delta$ WHR and CHR: difference between wrist heart rate and chest heart rate; CI: confidence interval; WHR: wrist heart rate.



**Fig. 2.** Bland-Altman plots of WHR and CHR in paretic side.

Solid line indicates mean  $\Delta$ WHR and CHR. Dashed lines represent upper and lower limits of agreement (LOA) of WHR and CHR. Lower and upper LOA were -20.8 beats/min and 21.6 beats/min, respectively. Pearson's correlation coefficient [95%CI] for mean and difference ( $\Delta$ ) between WHR and CHR was -0.08 [-0.11, -0.06] ( $p < 0.05$ ).

CHR: chest heart rate;  $\Delta$ WHR and CHR: difference between wrist heart rate and chest heart rate; CI: confidence interval; WHR: wrist heart rate.

**Table 3.** Intraclass correlation coefficients between WHR and CHR

	ICC (2.1)	95%CI	
		Lower	Upper
Non-paretic WHR and CHR	0.75	0.74	0.76
Paretic WHR and CHR	0.79	0.78	0.80
Non-paretic and paretic WHR	0.81	0.81	0.82

All ICCs were significant ( $p < 0.05$ ).

CHR: chest heart rate; CI: confidence interval; ICC: intraclass correlation coefficient; WHR: wrist heart rate.

This could explain the lower correlations between WHR and CHR in the present investigation, compared with previous studies.

In terms of absolute reliability as the precision of WHR, MAPEs were  $< 10\%$  on both non-paretic and paretic sides. This indicated that monitoring HR on non-paretic and paretic wrists offers a valid way to refer to cut-off points of MAPE  $< 10\%$ <sup>39</sup>. However, LOAs between WHR and CHR in Bland-Altman plots were large. These results indicate that the deviance of

differences between WHR and CHR was large. Previous studies analyzing differences in WHR and CHR yielded similar differences to our values<sup>16–20, 47</sup>. In terms of the validity of LOA, the acceptance value was less 15–20% between the current reference and new technique<sup>48</sup>. In our study, LOAs ranged by  $\pm 24$ –28% between WHR and CHR. This poor prediction ability might be attributable to motion artifacts<sup>29</sup>. In terms of systematic bias, fixed biases as differences in WHR and CHR were very small, and the 95%CI was associated with a small positive bias with WHR. Some reports have indicated that the mean difference between WHR and CHR ranged from  $-12.8$  to  $8.9$  beats/min, with a standard deviation ranging from 14.4 to 33.5 during rest, resistance training, activities of daily living and treadmill walking<sup>18, 19</sup>. Compared with past studies, the difference was not large in our study. This small bias might indicate that vasomotor dysfunction in vessels is not severe enough to present measurement of WHR among hemiparetic inpatients with stroke.

On the other hand, no significant proportional bias was observed by associations between difference and mean of WHR and CHR. The values of Pearson's correlations ranged from  $-0.11$  to  $-0.08$ , which would be interpreted as showing little or no correlation. These very weak correlations would be acceptable to use WHR monitors during physical therapy.

Paretic WHR was slightly accurate than non-paretic WHR in MAPE and difference between WHR and CHR. Patients with stroke exercised for longer periods for gait, sit-to-stand and pre-gait activity, indicating that the duration of functional training of a paretic upper limb is shorter than that of locomotor exercise<sup>49, 50</sup>. In addition, patients with stroke were in the post-acute phase and might have been able to use their non-paretic arm to support balance by holding on to walking aids. Difference of accuracy in paretic side and non-paretic side could be related with use of arm and hand support causing motion artifact<sup>46</sup>.

We included two patients with AF in the analysis of WHR monitors. Measuring HR might be more difficult in patients with AF, due to the theoretical technique applied to interpret sampling frequency and delayed pressure waveforms<sup>51</sup>. However, measuring HR using PPG is practical, and AF could be detected<sup>52, 53</sup>. In addition, WHR monitors are useful to manage AF and could measure the HR of patients with AF<sup>54</sup>. The MAPE of two patients with AF in the present study were 5.8% and 12.5% on the non-paretic side and 5.86% and 17.4% on the paretic side. These values were not particularly high compared with previous studies<sup>18, 47</sup>. Atrial fibrillation is usually treated during the acute phase, indicating stable HR control in these patients with post-acute AF. In the present study, motion artifacts or active exercise might have had more effect on HR difference than AF. However, the influence of AF on WHR monitoring was not clear from our study.

One limitation of this study was the synchronization of WHR and CHR. Setting precisely the same time for each device is difficult, because they have different algorithms for setting time. The HR generated by each device was sampled at slightly different times. Moreover, the reliability of the Polar A370 WHR monitor is not generalizable, because the accuracy of WHR monitors differs across devices<sup>20, 48</sup>. We did not determine the accuracy of WHR monitors for patients with arrhythmias such as AF, or generalize its reliability for patients with heart disease. Further studies are needed to explore the reliability of other devices and the benefits they might offer to patients with arrhythmia.

In conclusions, this study investigated the accuracy of WHR monitors compared with CHR monitors. The relative reliability of WHR was substantial compared with CHR. On the other hand, the absolute reliability as bias in WHR and CHR was small, but estimation of HR measured at the wrist was not particularly accurate because of the wide LOA. The fixed bias was very slight, but no significant proportional bias was observed in WHR. The wrist worn heart rate monitor has potential of improving rehabilitation quality measuring exercise intensity. Physical therapist would easily manage various exercise or activity intensity by wrist worn monitor.

### *Conflict of interest*

The authors have no conflicts of interest to declare.

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