Spontaneous Cardiac-Locomotor Coupling in Healthy Individuals During Daily Activities

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Abstract: During exercise, the locomotor and the cardiovascular system work in synergy to control the blood flow through the body. In particular, the muscle contraction generates rhythmic raising and lowering of intramuscular pressure, which in synergy supports cardiovascular function. This study aims to analyze spontaneous cardiac-locomotor coupling (CLC) events during daily activities using weareable sensors. We analyze the data set PMData, containing recordings from sixteen healthy subjects during five months. The data were acquired with a smartwatch and consist of step rate (SR), heart rate (HR) and daily surveys reporting the training sessions. Coupling is defined as being present when SR and HR are within 1% of each other (strong coupling) and within the 10% of each other (weak coupling). The results show that every subject presents occurrences of CLC while performing normal daily activities. In particular, strong coupling occurs more likely for longer activities (111 ± 34 min), at moderate intensity ($100\frac{steps}{min} < SR > 130\frac{steps}{min}$). The presence of CLC during daily activities rises the question whether there is a physiological mechanism controlling this phenomenon, that should be investigated in future.

1 INTRODUCTION

The human body is made of a set of systems that work in synergy to achieve maximum efficiency, within certain metabolic and bio-mechanical constraints. The cardiovascular, the respiratory and the locomotor system affect blood flow.

In fact, during locomotion, blood flow through the body is influenced by two opposing pumps. The pumping of the heart delivers the blood to the whole body and the skeletal muscle pump, through periodic increases of intramuscular pressure and venous return (Novak et al., 2007), pumps it back to the heart. If these two pumps become entrained, with equal contraction rates, the cardiac-locomotor coupling (CLC) phenomenon occurs (Niizeki and Saitoh, 2014).

Prior studies of CLC investigate the interaction between the cardiovascular and the locomotor system during rhythmic exercise in the laboratory setting (Kirby et al., 1989; Hausdorff et al., 1992; Constantini et al., 2018; Takeuchi et al., 2014). In the past, researchers used different signal processing techniques to identify the CLC during exercise. One method consists in processing the electrocardiogram (ECG) and the acceleration, identifying the rates and calculating the ratio between the heart rate (HR) and the step rate (SR) (Kirby et al., 1989). Another technique consists in analyzing the frequency spectrum and the coherence of the acquired signals (Hausdorff et al., 1992; Niizeki et al., 1993). It has been demonstrated that the HR increases when the muscle contraction is synchronized with the systolic phase of the cardiac cycle (Niizeki and Miyamoto, 1999). In contrast, if opportunely synchronized with diastole (see Figure 1), it can reduce the HR and the ventilation, indicating improved cardiac efficiency (Constantini et al., 2018).

All prior studies on CLC take place in controlled, monitored environments and study short-term activities such as walking and running on a treadmill or cycling (Nomura et al., 2003). However, the physiological occurrence of CLC remains elusive. In particular, we do not know if humans in their daily lives experience CLC, a necessary condition to allow for

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diastolic synchronization. Our hypothesis is that the CLC is a common occurrence across individuals, not only in laboratory settings but also during activities of daily life.

The use of smartphones and wearables has become common practice to record signals about physical activities and health status, called lifelogging (Karami et al., 2021). Exploiting this trend, this study aims to use lifelog data to analyze the extent of CLC occurrences during non-monitored daily activities, collected retrospectively from a wrist-worn wearable device. Moreover, we want to investigate how occurrence of CLC depends on the intensity, the type and the duration of the activity and subject-age.

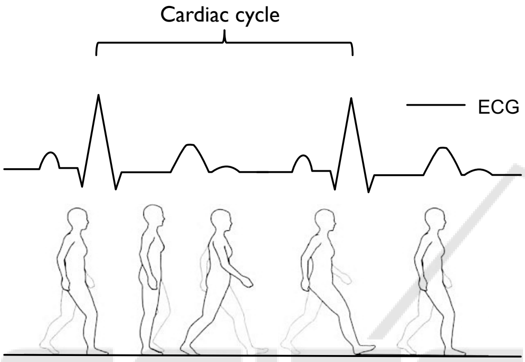

Figure 1: Timing of cardiac cycle and gait cycle during diastolic cardiac-locomotor coupling.

2 METHODS

2.1 Study Population

We used a retrospectively acquired dataset called PM-Data (Thambawita et al., 2020). The dataset contains data collected from 16 healthy subjects (13 men and 3 women), aged between 23 and 60 years (34.85 ± 11.67 years) (Table 1).

The participants were grouped into elderly and young to assess inter-class differences using a common threshold of 40 years of age. The elderly group presents 5 subjects (49.80 ± 7.22 years) and the young group 11 subjects (28.09 ± 4.64 years).

2.2 Study Protocol and Recorded Variables

The participants wore a Fitbit Versa 2 (Fitbit.Inc, San Francisco) for a period of 5 months, from November 2019 to the end of March 2020. They were encouraged to wear the smartwatch as much as possible. The study organizers did not impose any restrictions or requirements on the type or duration of exercise (Thambawita et al., 2020).

The Fitbit acquired SR per minute and HR per 5 seconds. Each entry has a timestamp that allows to synchronize samples from different files. Moreover, the participants were encouraged to use PM Reporter Pro smartphone application (Forzasys AS c/o Simula Research Laboratory, Oslo) to collect subjective assessments of training load, reported after every training session. The subjective assessments of training load are collected in CSV-files named Session Rating of Perceived Exertion (SRPE). Each SRPE file contains the type of activity performed, the training session's end time, the duration and the rate of perceived exertion (RPE), used to assess the internal training load.

2.3 Data Analysis

The files were processed in MATLAB R2022a (The MathWorks, Natick, MA) for all analyses. We used the Statistic and Machine Learning Toolbox.
Since the HR and the SR were not acquired with the same sampling rate, we first synchronized both signals using the timestamp information. The HR was averaged per minute, in order to match the time resolution of the SR and to account for possible fluctuation in HR due to potential fluctuations in device accuracy.

The data were filtered to instances of physical activity with the goal to delete instances of sleep and rest. We used the metabolic equivalent of task (METs) to evaluate physical activity intensity. One metabolic equivalent represents the oxygen consumption while sitting at rest (1 MET= 3.5 ml O_2/kg/min)(Jetté et al., 1990). We used a MET level of 2 and a threshold of 60 $\frac{steps}{min}$ as indicative of instances of physical activity, as this SR was previously identified as slow walking in a study population of adults older than 20 years of age. (Tudor-Locke et al., 2011). All data below 60 $\frac{steps}{min}$ were excluded from the analysis.

2.3.1 Cardiac-Locomotor Coupling

To find evidence of CLC, the ratio between SR and HR, defined as:

$$R = \frac{SR(\frac{steps}{min})}{HR(\frac{beats}{min})} \tag{1}$$

was computed for each entry. Coupling is defined as a deviation between SR and HR of $< 1\%$ (Kirby et al., 1989). We group the data into uncoupling (deviation $> 10\%$), weak coupling (deviation $< 10\%$) and strong coupling (deviation $< 1\%$) for further considerations. We introduced a new parameter to evaluate the deviation from the ideal ratio 1:1. We called this parameter coupling parameter and we defined it as follow.

$$C = \left|\frac{SR(\frac{steps}{min})}{HR(\frac{beats}{min})} - 1\right| \quad (2)$$

We used violin plot of the SR and the HR to look at their distribution. We decided to group the subjects in three groups, according to the number of step rates at which strong coupling occurred. In group 1, strong coupling occurred at one specific step rate, in group 2 at two step rates and in group 3 at three step rates.

2.3.2 Timing, Duration and Intensity

We analyzed the timing, the duration and the intensity of physical activities. For these calculations, we only used the dataset with SR and HR, which contains no information reported by the participant about which activity was performed.

We defined an activity as consecutive observations with a difference between them smaller than one hour. In this way, we were able to investigate the training habits and to calculate:

- the mean duration of activities
- the time of the day at which the activities were conducted

Furthermore, we stratified the data into three groups according to their heuristic cadence thresholds of 100 $\frac{steps}{min}$ and 130 $\frac{steps}{min}$ which are associated to moderate and vigorous intensity, respectively (Tudor-Locke et al., 2019; Tudor-Locke et al., 2020; Tudor-Locke et al., 2021). Hence, we divided the intensity of any activity in three different groups: light, moderate and vigorous activity.

2.3.3 Type of Training

We combined the information from the Fitbit and the one reported in the SRPE, described in the section 2.2. The reports about the training load contain four variables: end time of the training, type of training, duration and RPE. For each entry, the mean coupling parameter was calculated and the data were grouped according to two activities (running and strength training). Moreover, we computed the percentage of coupling for each training.

2.4 Statistical Analysis

Firstly, we plotted the distribution of the ratio to assess if coupling (1:1) was more likely then any other ratio. Then, a Chi-squared test was used to determine if the distribution of the ratio, coupling parameter, HR and SR is normal. Since these data were not normally distributed, we used nonparametric statistical tests to assess differences. Median and standard deviation were computed for each parameter of interest. For the amount of coupling, the timing and the percentage of occurrences, mean and standard deviation were calculated instead.

We chose the Kruskal-Wallis test to test statistically significant differences in grouping the subjects, according to their preferred SR, as explained in section 2.3.1. A Friedman test was instead used to assess statistically significant differences within the same group during different activities and coupling conditions. Pearson correlation coefficient was calculated to evaluate the relationship between HR and SR, median ratio and median coupling parameter and age. The results were considered statistically significant at $P \leq 0.05$.

3 RESULTS

3.1 Participant Characteristics

Demographic and physiologic data during strong coupling are summarized in table 1. The median HR during strong coupling ranges from 87 to 115 $\frac{beats}{min}$, with no statistically significant difference between the elderly and the young subjects. For each subject, there are between 683375 and 1819246 HR and SR entries acquired from Fitbit. No data from either HR or SR are missing. In the PM reporter app, instead, the participants registered less data, by adding from 2 to 113 training session. Moreover, only one subject did not record any training session.

3.2 Cardiac-Locomotor Coupling

Evidence of strong coupling was found in each subject. The distribution of the ratio is not normal, but centered around a subject specific median that ranges between 0.87 and 1. The median of the ratio over all subjects is 0.94. The centered distribution indicates that subjects prefer to adjust their SR and HR rather than those two quantities being independently controlled. Figure 2 shows the distribution of the ratio, plotted with different bin sizes, considering all the subjects during the entire observational period. By reducing the bin size, the peak at 1 becomes more evident. This result highlights how spontaneous strong coupling is prevalent during normal daily activities.

Table 1: Demographic characteristics of the participants, heart rate and step rate during strong coupling, coupling parameter and ratio. STD, standard deviation.

Subject	Age	Height	Gender	Heart rate		Step rate		Coupling parameter		Ratio	
				Median	STD	Median	STD	Median	STD	Median	STD
1	48	195	male	99.4	21.1	99	21.1	0.14	0.13	0.96	0.20
2	60	180	male	106	23.6	106	23.6	0.12	0.15	1.00	0.22
3	25	184	male	107	11.1	107	11.0	0.12	0.12	0.92	0.17
4	26	163	female	113	26.1	113	26.2	0.11	0.13	0.93	0.17
5	35	176	male	102	13.1	102	13.1	0.16	0.12	0.87	0.18
6	42	179	male	87.7	33.8	87	33.8	0.16	0.14	0.99	0.24
7	26	177	male	112	33.8	112	33.8	0.13	0.13	0.99	0.21
8	27	186	male	110	28.3	110	28.3	0.13	0.13	0.96	0.20
9	26	180	male	109	14.6	109	14.6	0.13	0.13	0.98	0.21
10	38	179	female	111	13.4	111	13.4	0.11	0.13	0.92	0.17
11	25	171	female	115	11.6	115	11.6	0.12	0.14	0.90	0.17
12	27	178	male	110	14.0	110	14.0	0.12	0.12	0.94	0.19
13	31	183	male	109	23.4	109	23.4	0.18	0.13	0.86	0.21
14	45	181	male	113	25.3	113	25.3	0.14	0.12	1.04	0.20
15	54	180	male	108	23.5	108	23.6	0.18	0.14	0.95	0.24
16	23	182	male	104	7.87	104	7.91	0.13	0.13	0.91	0.17

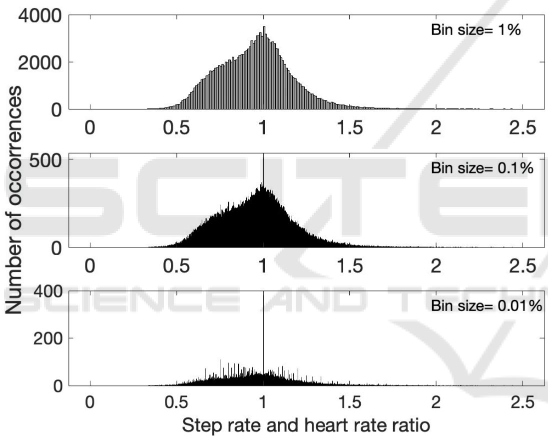

Figure 2: Ratio distribution.

The violin plots of HR and SR show that each participant has one, two or three different step rates at which strong coupling occur (Figure 3). This evidence was used to group the subjects, as presented in 2.3.1. We observe that group 1 includes 7 subjects, 28.4 ± 5.7 years; group 2 includes 8 subjects, 39.6 ± 13.7 years, and group 3 only includes one subject, 42 years old. Overall, it can be noticed that the total percentage of strong coupling occurrences is higher and the coupling parameter is smaller for the group 1 compared with group 2 and 3. However, no statistically significance was shown in any of the above mentioned parameters. The grey line in Figure 3 represents the threshold for moderate intensity activity. We can notice that for subjects 10 and 4, the strong coupling is prevalent when walking at a SR of $100\frac{steps}{minute}$ or more.

We found higher SR in instances of strong coupling vs. uncoupling (109 vs. 85, p=$4.4*10^{-7}$), and in instances of weak coupling vs. uncoupling (107 vs. 85, p=0.0028). Statistically significant difference was found also in the HR between the condition uncoupling and strong coupling (109 vs. 101, p= $6.02*10^{-4}$).

No correlation was found between the median of the ratio and the age or the height of the subjects. The same was found for the median of the coupling parameter and age and height.

3.3 Timing, Duration and Intensity

The following results present the differences found in the uncoupling, weak coupling and strong coupling occurrences among the subjects and the activities.

We found that each subject has a percentage of strong coupling occurrences ranging from 3% and 7% and a percentage of weak coupling occurrences ranging from 26% and 40%, calculated over the five months of observational period (Figure 4).

We noticed differences in the percentage of coupling occurrences between the young group (aged between 23 and 40 years) and the elderly group (aged between 40 and 60 years). Occurrences of weak coupling and uncoupling are significantly higher in the young group (33.61 vs. 36.19, p=0.0036 and 62,02 vs. 59.07, p=0.0068, respectively). No differences were found between the elderly group and the younger group as regard to the strong coupling (3.98 vs. 4.74, p=0.08).

The percentage of strong coupling occurrences (Figure 5) was significantly higher when perform-

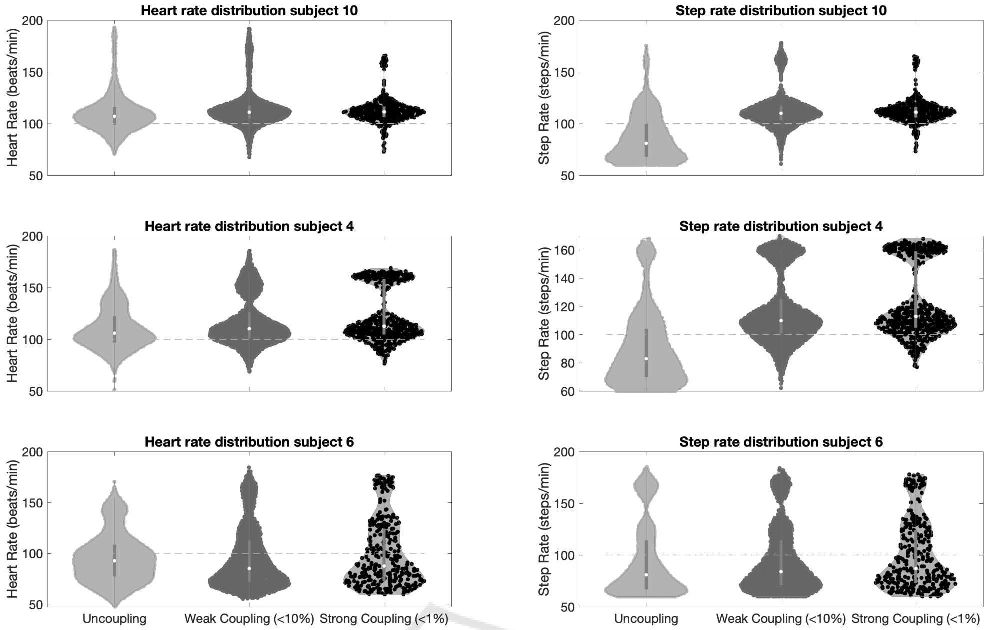

Figure 3: Violin plot of heart rate and step rate for three of the subjects.

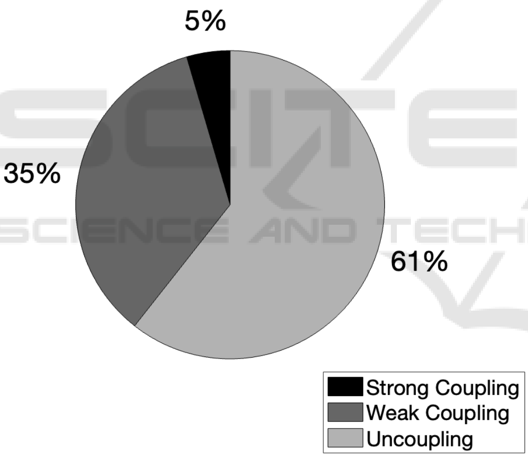

Figure 4: Coupling occurrences in percentage, mean for all subjects.

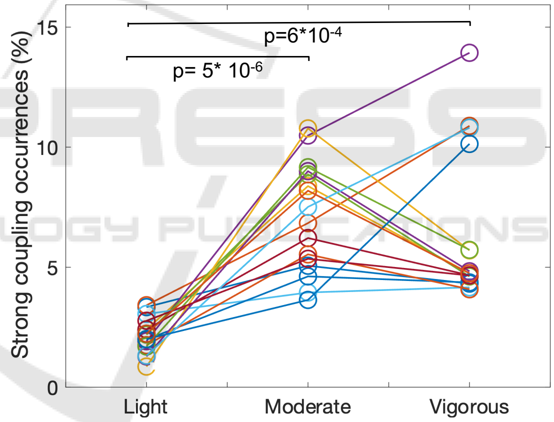

Figure 5: Percentage of strong coupling occurrences during different activity intensity for each subject.

ing moderate activities compared to light activities (7.17% vs. 2.10%, p=5.42 $*$ 10^{-6}) and when performing vigorous activities compared to light activities (4.745% vs. 2.10%, p=6.01 $*$ 10^{-4}).

The mean duration of activities (Figure 6) is significantly higher in presence of strong coupling events vs. uncoupling (111.31 vs. 69.89 min, p=4.4 $*$ 10^{-8}) in strong coupling vs. weak coupling events (111.31 in vs. 80.26 min, p=0.013) and in weak coupling events vs uncoupling (80.26 vs. 69.89 min, p=0.013).

We found no correlation between the time of the day at which the activity is performed and the coupling strength (12.89 vs. 13.10 vs. 13.00 , p=0.2 for uncoupling, weak coupling and strong coupling, respectively). In particular, most of the activity is distributed between 10h and 19h.

3.4 Type of Training

As regard to type of training, we found that coupling (both strong and weak) occurred to a larger extent during running exercises than during strength training (6.05% vs. 4.00%, p=0.004 and 39.30% vs. 27.50%, p=0.007, respectively).

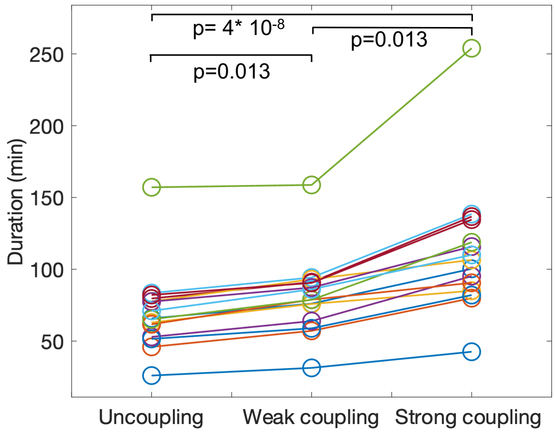

Figure 6: Mean activity duration for each subject.

4 DISCUSSION

Using lifelogging data, this study shows that every subject presents occurrences of CLC. Furthermore, the ratio 1:1 between SR and HR seems to occur more frequently than other ratios. Previous studies in laboratory settings claim that some of the subjects never coupled (Kirby et al., 1989; Novak et al., 2007; De Bartolo et al., 2021; Hausdorff et al., 1992). In particular, one laboratory study found that CLC occurred only in 18/25 subjects for step rates between 106 and 150 $\frac{steps}{minute}$ (Kirby et al., 1989). During daily activities, instead, we found a median SR between 87 and 115 $\frac{steps}{minute}$. The comparison of these two settings indicates that the SR of the subjects in the laboratory could be influenced by the use of the treadmill, which might affect the choice of a comfortable walking step rate.

When exercising, the cardiovascular system adapts to meet the metabolic demand of the systemic system including the skeletal muscles (Murphy et al., 2011). Physiology tells us that the interaction between cardiovascular and locomotor system originates in the interplay of the parasympathetic and sympathetic system. During muscle activity, the sympathetic nervous system is activated, which, in turn, increases the arterial blood pressure, the HR and the vascular resistance (Murphy et al., 2011). In this way, we expect the HR to rise with increasing in metabolic activity level, or increasing step frequency. The positive correlation between SR and HR was observed for all subjects in the present study. Additionally, we found that a 1:1 correspondence is most likely, which raises new research questions regarding the interaction of the cardiovascular and the locomotor system.

While previous studies focused only on the strong coupling, we also investigated when and to what extent the two rhythms were within 10% to each other (weak coupling). Even though the strong coupling is present only in the 5% of the observational period, during the 30% of the total time the HR and SR are within the 10% of each other. This result highlights that CLC can be reached without changing or forcing the physiology of the body.

In a laboratory study, they compared CLC during running and cycling and they demonstrated that CLC exists for longer periods during running compared to cycling (113.6s vs 58s, $p < 0.05$) (Nomura et al., 2003). Our analysis shows that coupling occurred to a larger extent during running compared to strength trainings. Running seems to enhance the CLC, compared to other training activities, which align with what we found during daily activities. Moreover, in the laboratory settings some subjects coupled only while running and not while walking (Kirby et al., 1989). The differences between the occurrence of CLC during walking compared with running, could be due to the duration of the laboratory experiment. In fact, with higher exercise intensity, the HR approaches the SR more rapidly than during walking (Kirby et al., 1989). In our study, we found that the duration of the activity is higher in presence of strong coupling (111 min$\pm$ 34 min), whereas in the laboratory study only 2-5 min of walking were performed (Kirby et al., 1989). However, we also found that there are some subjects who couple more while performing vigorous activities (SR $>$ 130 $\frac{steps}{minute}$) and other who couple more while performing moderate activities (SR $>$ 100 and $<$ 130 $\frac{steps}{minute}$), compared to light activities. The body seems to approach CLC rapidly when the exercise intensity is higher and slowly when walking at lower speed.

The extent and speed of sympathetic activation results in different HR effects depending on the subject level of training. In a trained subject, we expect the resting HR to be lower than in an untrained subject. The subjects in our study have a resting HR below 70 $\frac{beats}{minute}$, indicating a good level of training. During running, the trained subject is engaged in rhythmic exercises and we would more likely observe a stable 1:1 ratio between HR and SR. The observation we made regarding the number of SR at which strong coupling occur can be dependent on the training habit of the participants, rather than on the CLC effect. The study reports the time it took each subject to run 5km, however, we did not find the results very credible and therefore did not use them in this analysis.

The small size of our study population, characterized by only healthy subjects, limits any discussion concerning intra-subject characteristics, like age or height that may enhance or inhibit the CLC. In a previous study (Novak et al., 2007), they show that HR and SR were coupled only for the elderly group (70.3 ± 5.1 years) and not for the young participants (29.0 ± 5.0 years). In our study cohort, we found no differences in the extent of strong CLC between the participants aged <40 years vs. > 40 years old. However, the young cohort expressed higher extent of weak coupling. The reason could be due to the small number of elderly subjects, which consisted of 5 subjects (49.8 ± 7.2 years) in our study compared to 9 subject (70.3 ± 5.1 years) in the study (Novak et al., 2007). Further research including more subjects with an higher average age may be useful to investigate age-related physiological effects.

Smartwatches are a powerful tool to obtain insights and information about non-monitored daily activities, that would otherwise be difficult to obtain. However, the advantage of unsupervised data collection could translate in non-monitored artifacts in the data. One example could be detecting steps when the person is using the hands for other tasks, but is not exercising. Another could be that rhythmic movement of the wrist during exercise, induces wrongly detected heart beats. Furthermore, we expect motion related measurement artefacts to increase with activity level. However, most coupling was found at moderate intensity. The HR detection from a wrist-worn device relies on the photoplethsmography (PPG) signal, a technique that has various limitations compared to the chest-worn sensors, which rely directly on the electrocardiogram (Boudreaux et al., 2018). Tight compression of the device on the skin, changes in skin temperature and perfusion and contraction of skeletal muscle in the forearm and in the hand, are some of the cause of artifacts in the PPG signal that can lead to underestimation of HR (Boudreaux et al., 2018). In the future, a chest-worn device with higher accuracy, less prone to artifacts and more robust against HR measurements, should be utilized (Feehan et al., 2018; Chevance et al., 2022; Sjöberg et al., 2021).

The dataset included reports of step rates and heart rates. However, the reports did not allow a study of the synchronization of both time series signals with respect to each other. In particular, it would be interesting to understand if the subjects synchronized each step with the diastolic or systolic part of the cardiac cycle. Current wearable devices do not register the acceleration and cardiac signals on the same clock, which makes it harder to study such high time-resolution phenomena. In particular, no dataset exists that records these signals during daily activities. The identification of CLC events during every day activities presented in this work raises further questions to whether there is a physiologic mechanism that controls CLC. Unfortunately, the dataset lacked sufficient reports of perceived exertion during coupling and uncoupling and thus did not allow for investigation of physiological benefits of CLC in terms of exercise performance. In the future it should be investigated whether CLC could offer a more efficient way of training.

5 CONCLUSIONS

In conclusion, we found evidences of spontaneous CLC during daily activities in every subject. In particular, CLC occurs more likely when the subject engages in long activities at moderate intensity. Moreover, the ratio 1:1 between SR and HR seems to prevail over any other ratio. By improving the understanding occurrence of CLC in daily life, this work supports further research on customised training and rehabilitation programs. Future work will address the synchronization between cardiac contraction and the gait cycle using temporal and spectral signal analysis techniques.

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