



Université du Québec
à Rimouski

**LA FRÉQUENCE D'ENTRAÎNEMENT INDIVIDUALISÉE EN FONCTION DE LA VARIABILITÉ DE
LA FRÉQUENCE CARDIAQUE : UNE ÉTUDE ÉCOLOGIQUE D'EFFICACITÉ**

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PAR

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À la caféine, à l'angoisse existentielle
de la conciliation de deux emplois avec
une maîtrise à temps partiel et à mon
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AVANT-PROPOS

En 2019 (si ma mémoire est juste), alors que j'écoutais un *podcast*, j'ai entendu parler de la variabilité de la fréquence cardiaque. L'hôte du *podcast* parlait de la variabilité de la fréquence cardiaque à l'époque en tant que mesure éprouvée pour évaluer la récupération à l'entraînement musculaire et les effets de différents éléments du mode de vie sur le système nerveux autonome. Je connaissais très peu le sujet et je ne connaissais pas l'état de la recherche sur le sujet à ce moment-là. Je me suis demandé si l'hôte ne mettait pas « *la charrue devant les bœufs* ». La curiosité m'a piqué et j'ai commencé à me renseigner davantage, ce qui a mené à l'émergence de mon sujet de recherche l'année suivante.

RÉSUMÉ

La pratique de la kinésiologie s'est développée durant la pandémie de COVID-19, avec une augmentation des suivis en télésanté. Les kinésiologues disposent de peu d'outils objectifs pour mesurer la récupération de clients à la suite d'une charge d'entraînement. Le présent projet de recherche intitulé « *La fréquence d'entraînement individualisée en fonction de la variabilité de la fréquence cardiaque (VFC) : une étude écologique d'efficacité* » s'intéresse à la VFC en tant que mesure de récupération à l'entraînement musculaire en vue de bonifier les suivis de clients. Deux études ont été réalisées dans le cadre de cette maîtrise ; ces études ont été rédigées sous forme d'articles et soumises à des journaux avec comité de pairs. La première étude est une revue de littérature qui explore la thématique de l'utilisation de la VFC dans un contexte d'entraînement de la force musculaire. Cette revue démontre qu'il y a peu d'études sur le sujet et que les résultats des études sont hétérogènes et les résultats sont variables. La deuxième étude est une étude d'efficacité qui s'est intéressée aux variations de la VFC lorsque des participants entraînés ont été soumis à une charge de travail croissante, ainsi qu'à leur adhésion aux conditions d'entraînement. Ainsi, neuf participants (7 hommes, 2 femmes, âgés de $29,7 \pm 8,8$ ans, ayant au moins 24 mois d'expérience en entraînement musculaire) ont été recrutés. Une approche écologique avec des tests pré et post a été utilisée. Les participants devaient suivre un programme d'entraînement de la force en suivi à distance et transmettre des données quotidiennement au chercheur principal (VFC, données d'entraînement, questionnaire journalier). Les principaux résultats étaient que la VFC n'a pas varié de manière significative au cours des six semaines. Le protocole a entraîné des gains de force sans affecter de manière significative la modulation parasympathique. Également, l'adhésion au protocole était élevée si l'on la compare à différentes interventions auprès de la population générale. Plus d'études sont nécessaires pour évaluer les associations entre la VFC et d'autres mesures objectives et subjectives de récupération.

Mots clés

Récupération, outil d'entraînement, charge d'entraînement, suivi à distance

ABSTRACT

The practice of kinesiology developed during the COVID-19 pandemic, with an increase in online health coaching. Kinesiologists have few objective tools to measure clients' recovery following a training workload. The current project called: “*Frequency based on individualized Heart Rate Variability on a strength 6-week training program. A remote-coaching effectiveness study*”, focused on heart rate variability (HRV) as a measure of recovery from strength training in order to improve client follow-ups. Two studies have been conducted as part of this master's program; those studies have been written in the form of articles and submitted to peer-reviewed journals. The first study is a literature review exploring the theme of using HRV in the context of strength training. This review demonstrates that there are few studies on the topic and that the results of the studies are heterogeneous and variable. The second study was a feasibility study focused on how HRV varied when trained participants were subjected to a progressive training workload, along with their adherence to the training conditions. Therefore, nine participants (7 men, 2 women, aged $29,7 \pm 8,8$ years, with at least 24 months of strength training experience) were recruited. An ecological approach with pre- and post-testing was used. Participants had to follow a strength training program in a remote setting and transmit data to the leading researcher daily (e.g. HRV, training data, daily questionnaire). The main findings were that the HRV didn't change significantly over the six weeks. The protocol resulted in notable strength improvements without significantly affecting parasympathetic modulation. Additionally, adherence to the protocol was high compared to other interventions in the general population. More research is needed to explore the relationships between HRV and other subjective and objective recovery measures.

Keywords

Recovery, training tool, training workload, remote coaching

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LISTE DES ABRÉVIATIONS, DES SIGLES ET DES ACRONYMES

%1RM	Percentage of 1-repetition maximum (Pourcentage d'une répétition maximale)
ANS/SNA	Autonomic nervous system (Système nerveux autonome)
BL	Baseline (Niveau basal)
CV	Coefficient of variation (Coefficient de variation)
ECG	Electrocardiogram (Électrocardiogramme)
HF	High frequency band (Bande de haute fréquence)
HRC	Heart rate complexity (Complexité de la fréquence cardiaque)
HRV/VFC	Heart rate variability (Variabilité de la fréquence cardiaque)
IRR	Inter-repetition rest (Pause inter-répétitions)
LF	Low frequency band (Bande de basse fréquence)
LF/HF	Ratio of LF-to-HF power (Rapport LF/HF)
Ln	Logarithmic form (Forme logarithmique)
LOE	Level of evidence (Niveau de preuve)
n.u.	Normalized units (Unités normalisées)
NN	Normal-to-normal (Intervalles de temps normaux)
pNN50	Percentage of successive normal-to-normal intervals that differ by more than 50 milliseconds (Pourcentage des intervalles normaux successifs qui diffèrent de plus de 50 millisecondes)
PNS/SNP	Parasympathetic nervous system (Système nerveux parasympathique)

PPG	Photoplethysmography (Photopléthysmographie)
RIR	Repetitions in reserve (Répétitions en réserve)
RMS	Root-mean square (Moyenne quadratique)
RMSSD	Root-mean square of successive differences (Moyenne quadratique des différences successives)
RP	Rest-pause (Séries avec récupération partielle)
RPE	Rate of perceived exertion (Perception de l'effort)
RT	Resistance training
SD1	Poincaré plot standard deviation perpendicular the line of identity (Écart-type du tracé de Poincaré perpendiculaire à la ligne d'identité)
SD1/SD2	Ratio of SD1-to-SD2 (Rapport SD1/SD2)
SD2	Poincaré plot standard deviation along the line of identity (Écart-type du tracé de Poincaré le long de la ligne d'identité)
SDNN	Standard deviation of normal-to-normal intervals (Écart-type entre les intervalles NN)
SNS	Sympathetic nervous system (Système nerveux sympathique)
SDRR	Standard Deviation of R-R intervals
ST	Strength training
TRD	Traditional training (Entraînement traditionnel)
TRD-F	Traditional training to failure (Entraînement traditionnel à l'échec musculaire)
TVL	Training volume load (Volume d'entraînement : tonnage)

VL	Very low frequency band (Bande de très basse fréquence)
WL	Workload (Charge de travail)

INTRODUCTION GÉNÉRALE

L'entraînement musculaire offre une multitude de bénéfices pour la santé, notamment l'augmentation de la masse musculaire, l'augmentation de la densité osseuse, de la force musculaire ou de la puissance, ainsi qu'une amélioration de la sensibilité à l'insuline, une meilleure gestion du stress et une augmentation de l'estime de soi (Lopez et al., 2021 ; Casanova-Lizón et al., 2025). Ces bénéfices, qui sont en fait des adaptations physiologiques, biomécaniques et psychosociales, sont possibles grâce à une charge de travail adaptée et une récupération adéquate. Les bénéfices sur la santé dépendent de deux facteurs importants, soit la charge de travail et la récupération. Cette optimisation de ces deux facteurs permet de réduire les risques de blessures et de surentraînement afin de maximiser la progression des individus (Cruz et al., 2020).

Dans le cas où l'un de ces deux facteurs serait mal contrôlé, les individus peuvent n'avoir aucun effet bénéfique de l'entraînement ou présenter des effets indésirables (blessures, perte de motivation à s'entraîner, fatigue physique et/ou mentale) (Williams et al., 2017). Dans certains cas graves, des individus peuvent présenter des symptômes du syndrome de surentraînement ou de rhabdomyolyse (Kreher et al., 2012). Ce qui ajoute à ce défi est que l'optimisation de la charge de travail et de la récupération est hautement individuelle (De Oliveira et al., 2019).

Les kinésiologues disposent de certains outils ou méthodes pour optimiser la charge de travail et la récupération des individus. Dans certains cas, ces outils (et méthodes) sont peu précis ou archaïques, mais surtout, la majorité d'entre eux n'évaluent pas l'équilibre entre les deux facteurs. Il y a donc un besoin de mieux documenter l'optimisation de la récupération en fonction de la charge de travail (De Oliveira et al., 2019). En d'autres mots, les kinésiologues disposent de peu d'outils objectifs qui permettent d'évaluer l'adaptation et l'optimisation de l'entraînement de chaque individu (Thamm et al., 2019). Le besoin d'outils accessibles est donc bien présent chez les kinésiologues, surtout considérant l'émergence de la télésanté (ou suivi à distance).

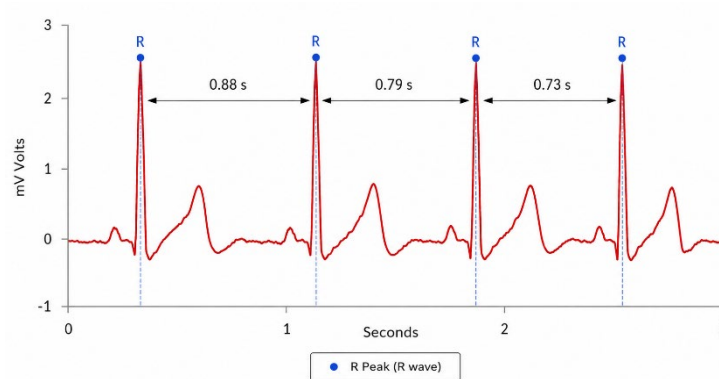
Avec l'essor des technologies portables, la variabilité de la fréquence cardiaque (VFC) a fait son entrée en tant qu'outil non-invasif pour évaluer les effets de l'entraînement aérobic sur l'état du système nerveux autonome (SNA) (Manresa-Rocamora et al., 2021). Dans le contexte de l'entraînement aérobic, il existe beaucoup de littérature scientifique sur l'optimisation de l'entraînement en utilisant la VFC (Manresa-Rocamora et al., 2021). Il a été documenté dans la littérature que cet outil aide à planifier l'entraînement en minimisant les impacts négatifs sur la modulation du SNA (équilibre entre charge d'entraînement et récupération). Il a été aussi suggéré que cet outil pourrait offrir une alternative pour la modulation de l'entraînement, et peut-être même mener à des bénéfices marginaux sur la condition physique ou la performance en comparaison avec l'entraînement aérobic traditionnel (Manresa-Rocamora et al., 2021). Il semble y avoir peu de littérature sur le sujet concernant l'entraînement en musculation modulé par la VFC. Le prochain chapitre présentera une revue de la littérature qui explorera le corps de la littérature sur le sujet.

Afin d'aider le lecteur à bien comprendre la VFC, il s'agit de la variabilité temporelle entre les battements cardiaques (entre les ondes cardiaques R). La VFC est donc une mesure indirecte de l'activité du SNA qui régule tous les processus corporels « automatiques » (circulation sanguine, respiration, digestion, température, etc.). Le SNA compte deux branches : la branche sympathique (SNS), responsable de la gestion du stress (« *fight or flight* ») et la branche parasympathique (SNP) qui répond à la relaxation (« *rest and digest* ») (Shaffer et Ginsberg, 2017).

La figure suivante présente une mesure temporelle entre trois battements cardiaques (Figure 1.), et la mesure de la variabilité « *pourrait être* » le calcul de l'écart-type entre les sommets (pics R) d'un électrocardiogramme (connu sous le nom de SDRR pour « *Standard Deviation of R-R intervals* ») sur une durée déterminée (par exemple 1, 3, 5 minutes). Ici l'expression : « *pourrait être* » signifie qu'il existe plusieurs types de calcul ou de variables pour quantifier la VFC (Shaffer et Ginsberg, 2017). Cependant, afin de ne pas complexifier le texte, un exemple du SDRR a été donné, car il s'agit d'une variable couramment utilisée dans la littérature et qui a été utilisée pour l'étude d'efficacité (étude 2). Voici un exemple de

l'utilisation de la VFC : à la suite d'un entraînement important, la VFC (ou SDRR) diminuerait, et augmenterait après quelques jours lorsque l'individu aurait récupéré de son entraînement.

Figure 1. Signal électrocardiographique illustrant les pics R.



Note. Figure créée avec l'outil d'intelligence artificielle générative ChatGPT

Dans le cas de l'entraînement musculaire, il a été démontré qu'à court terme, une charge d'entraînement importante diminuait la VFC (augmentation du SNS, diminution du SNP), et que lors d'une période de récupération appropriée, il y avait une augmentation de la VFC (augmentation du SNP, diminution de la SNS) (Chen et al., 2011 ; Cruz et al., 2020 ; De Oliveira et al., 2019 ; Figueiredo et al., 2015). Certains effets ponctuels sont donc connus, cependant le volume d'études qui utilisent la VFC à long terme en musculation est mince. Plus de données sont nécessaires pour mieux comprendre l'optimisation de la charge de travail à l'aide de cet outil. C'est pourquoi le projet de recherche associé à ce mémoire de maîtrise a pour but d'explorer l'efficacité d'un programme d'entraînement en force à fréquence d'entraînement individualisée basé sur la VFC, avec un encadrement à distance, sur une période de six semaines.

Ce mémoire, présenté sous forme d'articles, est structuré en 4 chapitres principaux correspondant à ; 1) une revue de littérature sous forme d'article (revue narrative) sur l'utilisation de la VFC pour l'entraînement de la force musculaire, 2) l'objectif de l'étude

incluant des compléments d'informations sur la littérature entourant le sujet, 3) l'article sur le projet d'intervention avec la VFC et 4) une conclusion qui propose une synthèse critique des travaux réalisés, les forces et limites de ce mémoire et une conclusion sur les retombées potentielles de la recherche au niveau clinique et scientifique.

CHAPITRE 1

REVUE DE LITTÉRATURE SUR LA VARIABILITÉ DE LA FRÉQUENCE CARDIAQUE ET L'ENTRAÎNEMENT EN FORCE MUSCULAIRE

Jean-Philippe Morin, Andrée-Anne Parent, Mathieu Tremblay. Titre : « *Is HRV a Tool for Monitoring Recovery from Strength Training?* ». Manuscrit soumis à : International Journal of Sports Science & Coaching (numéro de soumission : SPO-25-0544).

Résumé

Les kinésiologues et autres spécialistes de l'exercice individualisent des programmes d'entraînement pour leurs clients afin d'atteindre leurs objectifs individuels. Il est connu que le progrès en entraînement est uniquement possible quand la récupération à la suite d'un stimulus d'entraînement est adéquate. La variabilité de la fréquence cardiaque (VFC) reçoit de plus en plus d'attention en tant que mesure pour évaluer la réponse du système nerveux autonome (SNA) générée par la charge d'entraînement, mais le niveau de preuve est faible en ce qui concerne l'entraînement de la force musculaire. Le but de cet article était de réaliser une revue narrative de la littérature sur la VFC et la récupération en entraînement de la force pour explorer l'utilisation de la VFC pour mesurer la récupération à l'entraînement. Quatre bases de données ont été utilisées pour la recherche d'études avec des interventions en entraînement de la force dans les vingt-cinq dernières années (2000-2025). Seize articles ont été inclus dans la revue. Selon la littérature pertinente, il existe certaines preuves que la VFC est modulée par l'entraînement de la force à court terme. Il y a une quantité limitée de preuves en ce qui concerne les études longitudinales qui étudient la récupération de l'entraînement de la force en utilisant la VFC. Aussi, les interventions et les méthodologies étaient hétérogènes. Basé sur les résultats de la recherche, nous suggérons aux professionnels d'utiliser la VFC

afin de mesurer l'état de récupération du SNA à la suite de l'entraînement musculaire. La VFC pourrait être bénéfique lorsqu'utilisée en conjonction avec d'autres mesures de récupération ou de charge de travail (ex : échelles de perception de l'effort, questionnaires sur le sommeil ou le stress, journaux d'entraînement).

Abstract

Kinesiologists and other exercise specialists individualize training programs for their clients to meet their specific goals. It is known that training progress can only occur when recovery from the training stimulus is adequate. Heart rate variability (HRV) is getting more attention as a tool to monitor the autonomic nervous system (ANS) responses induced by the training workload, but the level of evidence is thin when it comes to strength training (ST). The purpose of this article was to conduct a narrative review of the literature on HRV and recovery from ST to explore the utilization of HRV to monitor the recovery from ST. Four databases were searched for studies with ST interventions in the last twenty-five years (2000-2025). Sixteen articles were included in the review. According to the relevant literature, there is some evidence that HRV is modulated by ST interventions in the short term. There is limited longitudinal evidence that HRV can monitor recovery from ST. Also, the intervention studies and designs were heterogeneous. Based on the results of this research, practitioners should use HRV to measure the ANS state of recovery from ST. HRV may be beneficial when used alongside other measures of workload or recovery. (i.e. RPE scales, sleep or stress questionnaires, training logs).

Keywords

Training tool, Recovery monitoring, Training workload, Training outcomes, Resistance training.

1.1 INTRODUCTION

As exercise science professionals, kinesiologists work with a wide array of populations with different needs, health histories and capacities. It is known that training adaptations and therefore training progress only occur when the individual can recover from a prescribed training stimulus.¹ It is important to notice that the adaptation to training workload (i.e. frequency, intensity, time, and type of exercise, volume, progression (FIIT-VP)) and the training recovery times are highly individual.^{2,3} Kinesiologists possess a few tools (e.g. Borg rating of perceived exertion (RPE), resting heart rate, logbooks, training apps, stress or sleep questionnaires) to help quantify or qualify the training workload or recovery of their clients. These tools have limitations and can lead kinesiologists to over- or under-train their clients.¹

Lately, heart rate variability (HRV) seems to be getting more attention as a tool to measure the influence of the training workload and recovery on the autonomic nervous system (ANS). More precisely, HRV is the time interval between consecutive heart beats. It measures the activity of two branches of the ANS: sympathetic (SNS) and parasympathetic (PNS).⁴ At rest, healthy individuals do not have a steady heart beat pace like a metronome, rather they have a variable time lapse between heart beats (translated by high PNS activity).⁴ HRV can be affected by a variety of physiological factors (e.g. chronic disease) and external stressors (e.g. emotional stress, pain). Strength training (ST) initially places stress on the body. As a result, a kinesiologist might observe lower parasympathetic nervous system (PNS) activity, indicated by decreased heart rate variability (HRV), in their clients immediately after strength training. This should return to baseline levels following adequate recovery. However, the volume of evidence is thin when it comes to understanding the impact of ST and recovery on HRV. The mechanisms associated with ST workload, recovery and HRV are not clearly identified, and its validity for assessing the level of recovery in the context of ST remains to be shown.

The current paper reviewed the last twenty-five years of literature from four databases to include both domains, specific (kinesiology) and general databases for a more thorough

search. The objective of this study was to explore the utilization of HRV as a measure of recovery from ST and as training modulation method. This paper could be useful to kinesiologists and other exercise science professionals for optimizing training prescriptions.

1.2 METHODS

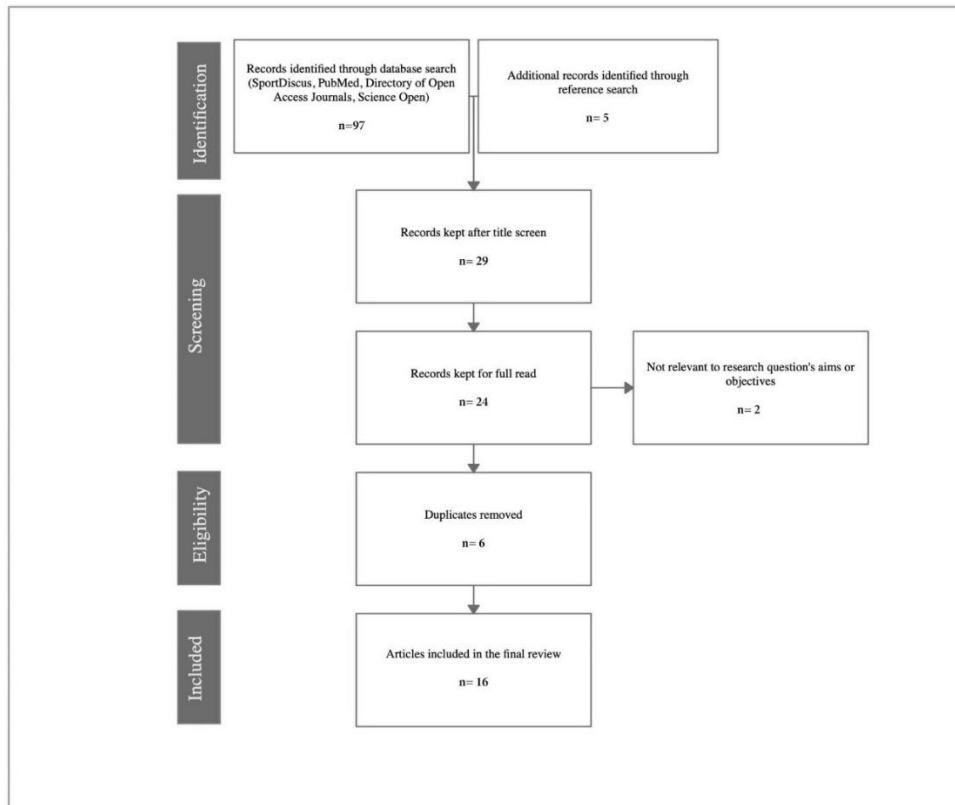
For this narrative review, a literature search from 2000 to 2025 was undertaken on SportDiscus, PubMed, DOAJ and Science Open. After conducting the search, references of the articles kept after full reading were screened for further references. For SportDiscus and PubMed, search terms were: ("*heart rate variability*" OR HRV OR "*heart beat*" OR "*autonomic nervous system*" OR "*vagal activity*" or "*vagal tone*") AND ("*strength training*" OR "*weight training*" OR "*resistance training*" or "*cardiovascular training*") AND ("*recovery*" OR "*fatigue*"). For DOAJ and Science Open, keywords were "*heart rate variability*", "*strength training*". English open access articles of any design or methodological quality were considered if they addressed HRV and a form of ST. Articles concerning specific populations whose conditions or context might affect autonomic modulation were excluded, notably obese individuals, elderly participants, post-contest bodybuilders, or participants with multiple sclerosis.

Titles were scanned by the authors to identify relevant elements. Abstracts then full texts were analyzed if deemed pertinent. Ninety-five studies were found, and sixteen studies were further analyzed and included in this narrative review (Figure 2). To further analyze the level of evidence, studies were graded using an approach from Sackett, Richardson and Rosenberg⁵ for the level of evidence (LOE). Studies were categorized as level I through V. Level I: systematic reviews, meta-analyses and randomized controlled trials; level II: two groups, non-randomized such as cohort and case control; level III: one group, non-randomized; level IV: descriptive studies with analysis of outcomes; level V: case reports or expert opinions including narrative reviews. Figure 1 presents the records identified through the database search. For analysis purposes, studies with six or more training sessions were

considered long-term, while those with fewer than six sessions were classified as short-term. Additionally, the analysis was limited to the PNS response to ST, to focus on the recovery.

To polish the writing and ensure fluidity, Grammarly Pro has been used to review the entire article. The methods flowchart was created using the Lucid Chart application, and the original image was updated with Paint Tool SAI v2 as more studies were added to the review in our 2025 update. The pie charts were made using Microsoft Excel. Chat GPT Plus was used to facilitate the conversion of the reference page to the Sage Vancouver format and to upgrade the resolution of the method flowchart to 300 DPI. Adobe Photoshop v26.4.0 was used to create grayscale versions of the figures.

Figure 2. Flowchart outlining the search process through databases.



1.3 RESULTS

Table 1 summarizes the training conditions in the studies and their effects on HRV, focusing on the PNS response to ST. Table 2 presents the HRV capture methods and the length of the studies (divided into short-term and long-term). Figure 3 presents the effects of ST on HRV in the short-term (i.e. five days or less). Figure 4 presents the effects of ST on HRV in the longer term (i.e. six days or longer). Appendix 2 presents detailed study summaries. Appendix 1 presents a summary of the other measures included in the studies (i.e. blood samples, aerobic fitness, performance, perceptive or neuromuscular measures (i.e. counter-movement jump, peak power, mean concentric bench press, squat velocity)).

HRV indices (or metrics) are divided into three categories: time domains, frequency domains and nonlinear measures. Each category includes measures related to the PNS's function. To facilitate understanding, Table 2 breaks down which systems the different measures refer to. HRV time domains, frequency domains and non-linear measures were documented in the corpus as follows: time domains (10 studies), frequency domains (8 studies), non-linear measures (5 studies). Most studies have used a combination of measures (see Table 2). Overall, PNS activity was the most documented with ST. RMSSD metric was one of the most widely used measures of the PNS. RMSSD is the root mean square of successive differences between normal heartbeats and reflects the beat-to-beat variance.⁴

Table 1. Training conditions in all the studies.

Authors	Condition	Set (n)	Rep (n)	Rest (s)	Exercises (n)	Intensity (%1RM or RM load)	Volume (n)	Training time(s)	Effects on PNS
Chen, et al. ¹	i.	5	1-3	90	4 (FB)	60-95%	48	7200	PNS↓ within 24h, BL at 48h
Cruz, et al. ⁸	i	1	11	60	3 (FB)	70%	33	279	PNS↓ between 1 st and 5 th min of recovery
	ii	2	11	60	3 (FB)	70%	66	558	
	iii	3	11	60	3 (FB)	70%	99	837	
De Oliveira, et al. ²	i. fixed frequency	3	9-12	120	8 (FB)	80%	Until failure	3636	PNS↓, BL at different intervals (24-48h or more)
	i. variable frequency	3	9-12	120	8 (FB)	80%	Until failure	3636	
Figueiredo, et al. ⁹	i	1	9	120	8 (FB)	70%	72	1176	PNS↓ at 10, 20 and 30 min for ii. and iii.
	ii	3	9	120	8 (FB)	70%	216	3528	
	iii	5	9	120	8 (FB)	70%	360	5880	
Flatt, et al. ³	i	6	Failure	90-120	3 (FB)	90%	4 RM to failure	2106	PNS↓, BL at 24h
Formalioni, et al. ¹⁸	i	2	Failure	45	3 (FB)	50%	20 RM to failure	630	PNS↓ for all time periods, no difference for conditions
	ii	3	Failure	90	3 (FB)	75%	10 RM to failure	1080	
	iii	4	Failure	180	3 (FB)	90%	4 RM to failure	2304	
Heffernan et al. ¹⁶	i. weeks 1-2	3	12-15	60-120	5 (FB)	60-70% to fatigue	202	1956	No difference in HRV
	i. Weeks 3-6	3	8-12	60-120	5 (FB)	70-80% to fatigue	150	1800	
Holmes et al. ¹⁴	i. mesocycle 1	3	10	60-90	6 (FB)	50-77%	180	1890	PNS↓ with increased weekly WL, non-significant
	ii. mesocycle 2	6	10	120	6 (FB)	50-77%	360	5400	
	iii. mesocycle 3	3-6	3-6	120-180	6 (FB)	70-90%	121	4413	

	iv. mesocycle 4	3-6	3-6	180	6 (FB)	70-90%	121	5223	
Holmes et al. ¹⁰	i. low volume	1-2	10	120-180	3 (FB)	70%	40	640	PNS↓ for all conditions, with a more significant decrease for conditions ii and iii.
	ii. medium volume	2-4	10	120-180	3 (FB)	70%	80	1280	
	iii. high volume	3-6	10	120-180	3 (FB)	70%	120	1920	
Iellamo et al. ¹⁷	i.	N/A	N/A	N/A	N/A (FB)	75-90%	90-100/day	N/A	PNS↑ with highest WL, non-significant at group level
Kassiano et al. ¹¹	i. TRD	5	12	180	1 (LB)	15 RM	60	900	PNS↓ for all conditions except for iii., more significant reduction for iv.
	ii. TRD-F	4	15	200	1 (LB)	15 RM		780	
	iii. IRR	1	60	10 between reps	1 (LB)	15 RM		770	
	iv. RP	1	60	30s between blocks after failure	1 (LB)	15 RM		N/A	
Mayo, et al. ¹²	i	5	8	180	1 (LB)	10 RM	40	1020	PNS↓ for i. vs control and pre values
	ii	10	4	80	1 (LB)	10 RM	40	920	
	iii	40	1	18.5	1 (LB)	10 RM	40	860	
Ramos-Campo, et al. ¹³	i. failure	4	10	90	2 (FB)	75%	10 RM to failure	840	No difference in HRV
	ii. not to failure	5	8(10)	90	2 (FB)	75%	2 RIR	840	
Schneider, et al. ¹⁵	i. am	12	6	30-180	3 (FB)	40-85%	72	5400	PNS↓ while supine
	ii. pm	16	6	30-180	4 (FB)	40-85%	96	5400	
Thamm, et al. ¹⁹	i	5	10	120	1 (LB)	80%	50	750	PNS↓, BL 30 min post
	ii	15	1	180	1 (LB)	100%	15	2745	
Williams, et al. ⁷	i.	N/A	N/A	N/A	N/A (FB)	N/A	Acute to chronic workload ratio	N/A	PNS ↓ with weekly WL tertiles

Note. Training time = (Total sets x rest times) + (total reps x 3 sec per rep unless tempo was specified). Tempo standardized to 3 sec total for concentric + eccentric phases if not mentioned. For sets to failure, repetitions were estimated with the NSCA RM chart. Abbreviations: Baseline (BL), Full Body (FB), Heart rate variability (HRV), Inter-Repetition Rest (IRR), Lower Body (LB), Not Available (N/A), Parasympathetic nervous systems (PNS), Repetition Maximum (RM), Repetitions in Reserve (RIR), Rest-Pause (RP), Sympathetic Nervous System (SNS), Traditional System (TRD), Traditional System to Failure (TRD-F), Workload (WL).

Table 2. HRV capture methods and observations.

Studies	Authors	Time between training sessions or times per week	Duration	Capture method and moments	PNS variables
Short-term	Chen, et al. ¹	N/A	1 session	- ECG 5 min seated after 5 min rest - Pre-ST, 3h, 24h, 48h and 72h post-ST	HF, LF, VLF
	Cruz, et al. ⁸	48-72h apart	3 sessions	- Polar V800 supine - Fast phase: between the 1 st and 5 th min of recovery. - Slow phase: at four 5 min intervals between the 5 th and 20 th min of recovery	SD1
	Figueiredo, et al. ⁹	72 hours apart	3 sessions	- Polar RS800CX seated 5 min - Pre-ST (after 10 min rest) and at 10 min intervals for 60 min post-ST	RMSSD, HF n.u., LF n.u.
	Flatt, et al. ³	N/A	1 session	- Polar H10 standing and supine - 5 days BL - 1 min recording after 1 min stabilization - 5 min pre-ST and 2 mornings post-ST	lnRMSSD
	Formalioni, et al. ¹⁸	35-7 days apart	3 sessions	- Polar RS800CX 5 min in dorsal decubitus - Pre-ST, soon after ST and 24h post-ST	RMSSD, HF, LF, VLF, SD1
	Holmes et al. ¹⁰	72h apart	3 sessions	- ECG seated 10 min segment pre-ST - ECG seated 30 min segment post-ST - ECG separated in 5 min segments	LnRMSSD
	Kassiano et al. ¹¹	7 days apart	4 sessions	- Polar H10 - 5 min seated after 10 min rest pre-ST - 5 min seated at 30 min post-ST	RMSSD, pNN50
	Mayo, et al. ¹²	72h apart	3 sessions	- ECG seated, breathing in semirecumbent position - 10 min pre-ST, 20-40 min post-ST	LnRMSSD, LnHF, LnLF
	Ramos-Campo, et al. ¹³	72h apart	2 sessions	- Polar H7 - During the 4-hour sleep period starting 30 min after bedtime - No control night	LF, HF, pNN50, RMSSD

	Thamm, et al. ¹⁹	7 days apart	2 sessions	- ECG supine 10 min - Pre-ST, immediately after (post0), 30 minutes post (post30), 1 hour post (post1h), 24 hours post (post24h), and 48 hours post (post48h)	RMSSD, LF, HF
Long term	De Oliveira, et al. ²	(2-4 days apart; 20 sessions total)	5 to 7 weeks	- Polar S810i, Polar Vantage supine 10 minutes - BL (5 days) - At the same time of the day	RMSSD
	Heffernan et al. ¹⁶	3 times per week	6 weeks	- ECG HRV 15 minutes supine - At BL (Pre1), after a 4-wk time-control period (Pre2), after a 6-wk ST intervention (Post1), and after a 4-wk detraining period (Post2).	HF, LF HRC
	Holmes et al. ¹⁴	3 times per week	18 weeks	- Smartphone PPG seated 1 min - Every morning	lnRMSSD
	Iellamo, et al. ¹⁷	3 times per day, 6 days a week	4 months + tapering	- ECG supine 10 min - BL after 4 weeks of detraining - 4 data points	HF, LF
	Schneider, et al. ¹⁵	11 times in 6 days	6 days	- Polar RS800CX - Active orthostatic test (7 min supine, 5 min standing) - BL after 3 days rest - Every morning	lnRMSSD
	Williams, et al. ⁷	N/A	16 weeks	- Smartphone PPG supine 1 minute - Every morning	lnRMSSD

Note. Abbreviations: Baseline (BL), Heart Rate Complexity (HRC), Heart rate variability (HRV), High frequency band (HF), Ln (Natural logarithm), Low frequency band (LF), Normal to normal beat intervals (NN), Normalized units (n.u.), Parasympathetic nervous systems (PNS), Percentage of successive RR intervals that differ by more than 50 ms (pNN50), Photoplethysmography (PPG), Poincaré plot standard deviation along the line of identity (SD2), Poincaré plot standard deviation perpendicular the line of identity (SD1), Ratio of LF-to-HF power (LF/HF), Root mean square of successive differences between normal heartbeats (RMSSD), Standard deviation of NN intervals (SDNN), Sympathetic nervous system (SNS), Very low frequency band (VLF), Workload (WL).

Figure 3. Short-term effects of ST on PNS (assessed with HRV)

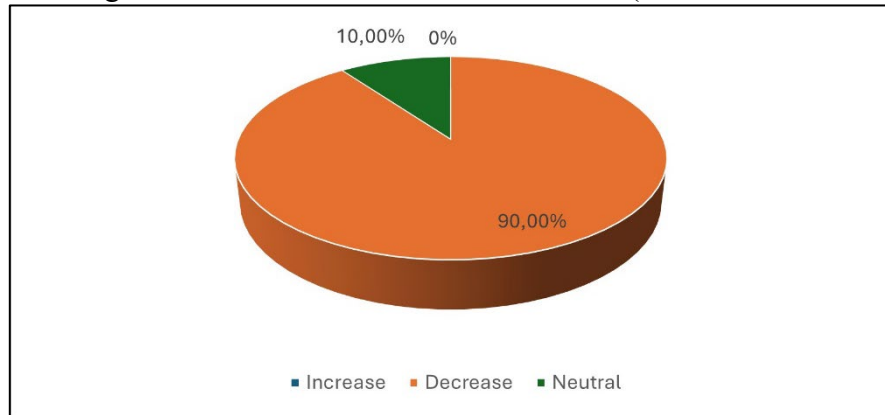
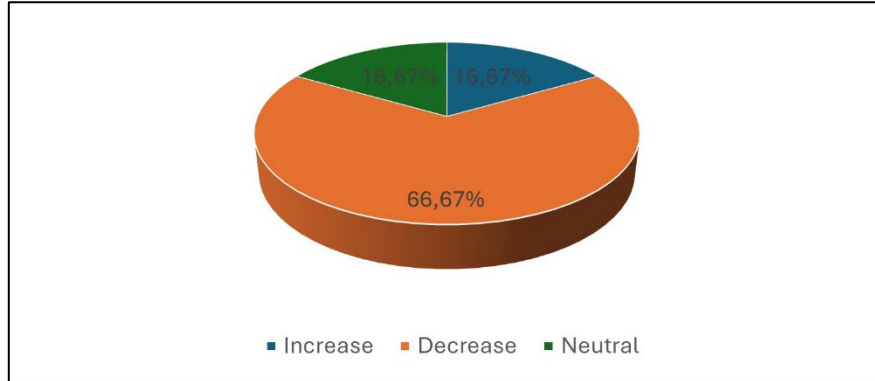


Figure 4. Long-term effects of ST on PNS (assessed with HRV)



1.4 DISCUSSION

The main goal of this review was to explore the use of HRV as a measure of recovery from ST and to examine its use for ST modulation. The following section is broken down into sub-sections to better address different topics.

1.4.1 Training workload and HRV

Balancing training workload with adequate recovery is the key to ensuring progression while minimizing the risk of suboptimal training or injury.^{3,6,7} One of the main topics was ST workload and its effects on HRV. In the corpus, training volume was the most documented parameter. In most studies, ST decreased PNS activity, both acutely and in the longer term (see figures 3 and 4). In fact, one recurrent finding in short term studies was that higher volume conditions (i.e. higher number of sets and repetitions) led to a decrease in PNS activity in the short term compared to lower volume conditions in trained and untrained men.⁸⁻¹¹ PNS activity was sensitive to more sets within a session (i.e., 8 and 12 sets led to a more significant reduction of HRV than 4 sets).¹⁰ Furthermore, short-term reductions in PNS were observed when sets were taken closer to failure at 10 RM (e.g. 8 reps led to lower HRV than 4 reps).¹² Also, intensity techniques such as rest-pause, which leads to increased training density (e.g., more volume within the same time frame), led to a more significant reduction of PNS than inter-repetition rest configurations or traditional ST taken to failure or not to failure.¹¹ These findings are in line with the fact that lower intensity training has less impact on heart hemodynamics.¹² Only one short-term study showed no difference in nighttime HRV with ST.¹³ In that particular study, the participants were highly trained, it is possible that they were well-adapted to the workload.

Four out of six longer-term studies (see figure 3) observe that chronic exposure to ST led to a reduction of PNS activity,^{2,7,14,15} with some evidence that the PNS activity decrease was greater in periods of increased workload.^{7,14} Although the results were not consistently significant throughout the studies.¹⁴ For instance, one study showed no difference in HRV

with chronic exposure to ST, but no information about the daily fluctuations of HRV with ST was provided.¹⁶ Also, one study in elite weight-lifter athletes documented an increase in HRV (i.e. PNS activity) at very high training volumes,¹⁷ but they did not rule out the potential effects of overtraining on the ANS. There were concerns about the analysis of the outcome because the participants trained very frequently (e.g. 18 times per week).

Overall, there is some short-term evidence and limited long-term evidence that HRV can be reduced by modulating ST workload. It is still important to bring some nuance to these observations because even though HRV was decreased in the short-term in most studies (see figure 2), some studies didn't observe differences between different conditions. When sets were taken to momentary failure, there was no difference between 2, 3 and 4 sets protocols, meaning that additional failure sets did not further decrease HRV.¹⁸ Also, when comparing hypertrophy and strength protocols in the short-term, similar decreases of HRV were observed in one study.¹⁹ Thus, the evidence suggests that HRV is affected by ST workload in short-term but might not be able to detect marginal changes in the training workload (e.g. training close to failure or to failure, changing repetition schemes when workload is equated).

Amongst all the body of literature, only one study documented variable training frequency with HRV.² It compared two groups: i) traditional ST with 3 times per week, and ii) an individualized frequency group. One of the main findings was that the individualized frequency group showed the same adaptations in a shorter time than the traditional ST group.² An interesting finding that wasn't further addressed by the authors was that the individualized frequency group recovered faster than the traditional ST group, according to HRV data.² When the training frequency increases, the total workload increases, therefore it is expected that the group training at higher frequencies would have lower HRV. The reasons why that happened are still unknown. Over the long term, increased frequency, guided by HRV, could represent a tool that optimizes and also increases the total workload (when athletes are fully recovered). This provides some evidence that HRV can be a tool to help better optimize the volume and limit maladaptation to training.^{2,6} More evidence is necessary to confirm this statement.

1.4.2 Time frame for recovery of PNS

It is known that the time required to recover from a ST session is highly individual.^{2,3} With time frames varying between 5 to 15 minutes to more than 48 hours after the session, it appears that the time frame for full PNS recovery from a single ST session is also variable and individual.^{1,2,13} The differences in the study designs made the analysis of this outcome difficult. In fact, only a few studies included HRV monitoring up to 24 hours in the post-workout (see table 2). Many individual and study design factors might influence the extent of the impact of ST on HRV and the time necessary for a full recovery (e.g. training time and total workload, training experience of participants, number of data collection points, data collection methods).^{1,13,16}

1.4.3 Baseline assessments, data points and capture methods

Comparing the daily HRV measurements relative to baseline allows to measure the adaptation of the PNS to the training load^{6,7}, and it is known that longer-term baseline assessment limits the impact of the daily fluctuations of HRV. A baseline assessment may require multiple days of rest. However, the best practices for baseline assessments of HRV with training are not well-known.⁶ Twelve of the sixteen studies included a single-measure baseline assessment or did not document how baseline HRV was collected. Only 2 studies have used a rolling 5-day average of HRV before the experimentation.^{2,3} Thus, it remains difficult to compare the outcome because the baseline context is required. In other words, rigorous and steady recording conditions are necessary to evaluate the influence of ST on HRV.

It is important to notice that two distinct types of studies were included: 1) studies evaluating the short-term effects of a training protocol on HRV and 2) studies evaluating the effects of long-term exposure to ST on HRV. For comparison, this means the indexed studies had different goals and were heterogeneous. In the corpus, 8 studies evaluated HRV for 72 hours or less, with 7 of them evaluating the effects of ST on HRV up to 48h post-workout

only. Longer-term studies lasted between 6 days and 18 weeks. Two of the 6 longer-term studies included limited data points analysis (4 data points over several weeks), and 4 studies were longer-term studies that included daily measurements in the same conditions. As previously discussed, short and long-term measurements serve different purposes. For evaluating the long-term effects of ST on HRV, regular data capture is desired, and averaging the measure (e.g., weekly averages) may diminish the impact of daily fluctuations on analysis.^{6,7,14} The studies with only limited data points provided little information about the impact of long-term exposure to ST^{16,17}, considering that the method used only a snapshot of HRV at one point in time. It did not account for potential daily spikes in HRV. This means that daily measurements under the same conditions are advised.

Across the 16 studies, the recording positions were as follows: supine only (8 studies), seated only (6 studies), standing and supine (orthostatic test) (2 studies). It is known that the supine HRV measurements increase parasympathetic tone²⁰ and standing measurements may cause parasympathetic withdrawal, because of the orthostatic stress. Flatt et al.³ reported that standing HRV showed stronger associations with other recovery markers (e.g., squat mean concentric velocity, perceptual recovery scale, perceptual soreness scale) than supine HRV. However, the relationships were not consistent in time and were non-significant, because there were no associations between the recovery time of HRV and the recovery time of other systems (e.g. neuromuscular). To our knowledge, seated HRV is less documented in the literature. The four studies using it did not explain their rationale. It is possible that the position is more convenient in practical settings for acute HRV measurements. Based on the current evidence, it is not known what the ideal position would be to measure recovery from ST using HRV.³

1.4.4 Breathing

Out of the 16 studies, only one controlled for breathing.¹⁶ They set the breathing pace at 12 breaths per minute. Some studies referenced spontaneous breathing, while others did not account for breathing at all. Even though it is known that breathing rate can affect some HRV metrics⁴, it is difficult to estimate its impact considering the wide variety of protocols. The use of spontaneous breathing or paced breathing should be documented in further studies, because it has a non-negligible influence on ANS fluctuations due to the accentuation of respiratory sinus arrhythmia during data collection. Some HRV measures, namely the HF band, are strongly influenced by breathing manipulations.

1.4.5 Associations between HRV and other measures.

Other measures were diverse and are detailed in table 3. The main association found was that in a cohort of elite athletes, lower HRV was linked to a greater risk of overuse injury.⁷ In fact, when HRV was low and the workload was high, the risk of injury was greater. Multiple other associations have been studied, but the results were less eloquent. Associations between heart rate variability and performance measures, such as VO2 peak, maximum isometric voluntary contraction, one-repetition maximum test, repeated sprint ability, and intermittent aerobic performance, were found to be weak or inconsistent.¹⁵ Associations between HRV, neuromuscular measures (counter-movement jump, peak power, mean concentric bench press, squat velocity) and perceptive measures (soreness, recovery) were weak or inconsistent.³ Time frames for the recovery of neuromuscular and HRV measurements were also highly individual.^{2,3} Furthermore, no association were found between HRV, muscle pain and creatine kinase.^{1,19} Overall, there was no evidence that HRV may be associated with muscle damage, neuromuscular fatigue or performance measures. The relationships between sleep quality and HRV with ST were not well-documented (1 study), however HRV and sleep quality weren't affected by a single session of training to

failure or non-failure in trained athletes, despite performance being affected 24h after training to failure.¹³ This information suggests that HRV may not be used as an analogous measurement for the state of recovery of other systems. This also means that HRV might provide additional information about recovery that other measures do not provide.

1.5 LIMITATIONS

There are limitations to this narrative review, namely because of the diverse study protocols and the level of evidence (see Appendix 1). Most studies did not mention if they controlled other factors that might have affected the HRV metrics (e.g. sleep, food or water intake, RPE, subjective well-being, sleep scale, stress inventory, allostatic load).¹⁹ Most of the studies were short-term, evaluating the acute effects of a single bout of training on HRV, therefore more studies are required in the long term to evaluate the effects of constant exposure to a prescribed workload. Also, most studies did not follow gold-standard capture methods (e.g. rigorous baseline assessment and regular methods under controlled conditions).

Across the studies, the participants were heterogeneous. Some of the studies included in the review had untrained participants (3 studies), while most had trained participants (11 studies). Three studies were on elite athletes.^{1,7,17} To our knowledge, the differences in HRV response to ST between trained and untrained populations are not well-documented. However, it is known that trained and untrained populations may respond differently to a training load⁶ considering that trained individuals are adapted to a certain training load and untrained populations are not (e.g. novel stimulus).¹³ The same training load could elicit greater training stress in untrained versus trained individuals. Furthermore, in some studies showing small effects of training on HRV, training load was modest, as shown by volume and training time in Table 1.^{12,19} If the training volume prescribed in the studies was inferior to the usual training load of participants (especially if trained), it is likely that no effect was observed, because the participants were well-adapted.

There are also some challenges with the data from studies. One study reported parasympathetic dominance in high-level athletes with very high training volumes.¹⁷ It is known that over-training leads to hormonal changes creating autonomic imbalances²⁰; however, the body of literature (mainly male samples) didn't allow us to analyze sex differences. Kuipers and Keizer²¹ hypothesized that advanced-stage overtraining led to sympathetic withdrawal and parasympathetic dominance (e.g. an inverted curve in response to very high training demands).²¹ Overall, HRV could be a valuable indicator of the PNS response for ST adaptation. However, its application is limited by inconsistencies in research findings, with current studies facing methodological gaps and wide participant diversity.

1.6 FURTHER RESEARCH

The current review provides some evidence that HRV can be modulated by ST workload and recovery, despite some inconsistencies and non-significant results. Further research is needed to determine best practices for measuring HRV baseline and consistently tracking daily data, as well as identifying which metrics to use. Given that various factors can influence HRV activity (e.g., lifestyle habits or mood states), a holistic approach should be emphasized to better understand the impact of real-life factors on PNS.

1.7 CONCLUSION

To conclude, this narrative review of the available literature on HRV and strength training was conducted across four databases. Few recent studies explored the effects of chronic exposure to strength training across populations. Research suggests that short-term responses to strength training may influence HRV. However, there is limited long-term evidence that HRV can effectively track responses to strength training. The main issue was that the protocols (training protocols and HRV data collection protocols) as well as the populations were heterogeneous. Currently, it is difficult to draw conclusions about standard practice for the use of HRV in the realm of strength training. Additional research is needed to develop a more effective training-monitoring tool for strength training practitioners.

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1.9 APPENDIX

Appendix 1: Other measures.

Studies	Measures
Chen, et al. ¹	- Blood samples: DHEA-S, creatine kinase - Perception: muscle pain
Cruz, et al. ⁸	- Vital signs: Respiratory rate - Performance: 1 RM test (bench press, leg press, barbell row)
De Oliveira, et al. ²	- Anthropometry: Muscle thickness (ultrasound of vastus lateralis) - Performance: 1 RM test (leg extension)
Figueiredo, et al. ⁹	- Performance: 1 RM test
Flatt, et al. ³	- Performance: 10 RM test (squat, bench, lat pulldown) - Neuromuscular performance: counter-movement jump, peak power, mean concentric bench press, squat velocity - Perception: perceptive recovery and soreness scale
Formalioni et al. ¹⁸	- Blood samples: lactate concentration, creatinine kinase - Perception: RPE
Heffernan, et al. ¹⁶	- Performance: 1 RM test (bench press) - Performance: Maximal aerobic testing (cycle ergometry) - Anthropometry: air-displacement plethysmography - Blood samples: fasting glucose, cholesterol, triglycerides
Holmes et al. ¹⁴	- Perception: RPE - Performance: 8 RM test (back squat, bench press, conventional deadlift) - Performance: estimated 1 RM - Performance: 3 RM post-test
Holmes et al. ¹⁰	- Anthropometry: height, weight, body fat (skin fold calipers) - Performance: 1 RM test (back squat, bench press, bent-over row)
Iellamo et al. ¹⁷	N/A
Kassiano et al. ¹¹	- Perception: Total quality recovery scale, RPE - Performance: 15 RM (parallel back squat)
Mayo, et al. ¹²	- Neuromuscular fatigue: Mean velocity - Performance: 10 RM test

Ramos-Campo, et al. ¹³	- Sleep monitoring - Sleep Diary
Schneider et al. ¹⁵	- Aerobic fitness: VO₂ peak (Treadmill with gas exchange) - Performance: Maximum voluntary isometric contraction - Performance: 1 RM test (parallel squat) - Performance: repeated sprint ability - Performance: intermittent aerobic performance
Thamm, et al. ¹⁹	- Performance: 1 RM test - Blood samples: creatine kinase - Perception: muscle pain
Williams, et al. ⁷	- Perception: RPE - Musculoskeletal: Overuse Injury Questionnaire
Abbreviations: Dehydroepiandrosterone Sulfate (DHEA-S), Rate of Perceived Exertion (RPE), Repetition Maximum (RM), Peak Oxygen Uptake (VO ₂ peak).	

Appendix 2. Study summaries.

Studies	LOE	Sample	Summary
Chen, et al. ¹	Level III	7 weightlifters (aged 19.3 +/- 0.3 years), 6 years of experience or more at national or international levels	Evaluated the HRV responses to a 2-hour bout of exercise. Following 10 days of detraining, 7 subjects underwent a session with 4 different exercises: back squat, seated shoulder press, deadlift and front squat. The athletes attempted each lift 3 times at 60% 1 RM, 3 times at 70% 1 RM, 3 times at 80% 1 RM, 2 times at 90% 1 RM and 1 time at 95% 1 RM with 90 seconds rest intervals. They monitored HRV before training and after 3, 24 and 72 hours of recovery. The HRV measures suggested that this group of elite weightlifters were fully recovered 48

			hours after the session (using parasympathetic measurements). Muscle pain measurements were back to baseline 72 hours after the training bout. The authors did not find a relationship between PNS activity and other recovery markers (i.e. muscle pain and creatine kinase). This provides information about the length of recovery in Olympic weightlifters after a single 2-hour training session.
Cruz, et al. ⁸	Level III	10 men with little to no strength training experience (aged 25.5 ± 4.9 years)	Compared three conditions. Conditions were i) one, ii) two and iii) three sets of bench press, leg press and barbell row. The load was set at 70% of 1 RM for sets of 10 to 12 with 60 seconds rest intervals. The study compared the effects of the three conditions on HRV. They monitored HRV in the supine position. SD1 was monitored between the 1 st and 5 th minute of recovery. SD2 was monitored at four 5 minutes intervals between the 5 th and 20 th minutes of recovery. Their results showed that the post-workout PNS activity was influenced by the volume and the time in the short term. The third condition (i.e., more sets and time) led to the lowest PNS activity. This provides information about the impact of increasing volume on the ANS.
De Oliveira, et al. ²	Level II	22 young men	Was the only study addressing the topic of training frequency based on HRV. They used a program with fixed exercise order. Exercises were: leg extension, incline leg press, leg curl (knee flexion), bench press, lat pulldown, triceps pushdown, arm curl and shoulder press. All exercises

			were performed for 3 sets of 9 to 12 rep around 80% of 1 RM. They had a group with fixed training frequency (3 times per week) and a group who was instructed to train or not to train based on the HRV values compared to baseline. The lower limit was set at one standard deviation below baseline. The study lasted 20 training sessions. PNS activity measurements with RMSSD were taken at the same time of the day in the laboratory, resting in supine position for 10 minutes. With this protocol, the group with the individualized training frequency completed the 20 training sessions in a shorter amount of time (5.1 weeks). The muscle and strength gains in both groups were similar and the authors concluded that utilizing HRV in strength training allowed an increased training frequency but wasn't a good indicator of training strain or training adaptations. The authors highlight that individualized recovery periods allowed to have the same adaptations in a shorter time frame. This may have further implications for kinesiologists to personalize training frequency.
Figueiredo, et al. ⁹	Level III	11 men with more than 6 months of strength training experience (aged 26.1 +/- 3.6 years)	Compared three set conditions i) 1, ii) 3 or iii) 5 sets with the same exercise order. The exercise order was: bench press, lat pulldown, shoulder press, biceps curl, triceps extension, leg press, leg extension and leg curl. The training sessions were 72 hours apart. They monitored HRV seated at rest 10 minutes before and at 10 minutes

			intervals for 60 minutes after the sessions. They measured the PNS activity with RMSSD values and HF-nu (high frequency band in normalized units) (19) along with SNS activity with the low frequency band in normalized units (LF-nu). They found that the session with the highest volume and time (i.e. 5 sets) led to the most significant decrease in PNS activity compared to baseline (pre-training). This means that similar results were reported in men with some strength training experience and in untrained men.
Flatt, et al.¹⁹	Level III	10 men with more than a year of strength training experience (aged 24.4 +/- 4.5 years)	Monitored the associations between HRV, perceptual recovery and neuromuscular fatigue. The study duration was 4 laboratory visits. The first session included initial testing. The second session included the experimental ST session, five days after. The subjects performed 6 sets to failure at 90% of 1 RM on three exercises. The exercises were squat, bench press and lat pulldown. The rest between sets was between 90 seconds and 2 minutes. HRV was monitored upon waking. They tracked PNS activity (LnRMSSD ultra-short (1 min recordings)). This process was done for 5 days to establish baseline and two mornings post-intervention. Data was collected standing and supine. They added neuromuscular measurements in the form of: counter-movement jump peak power, mean concentric bench press and squat velocity. Perceptive measures were perceived soreness scale (PSS) and

			perceptive recovery (PRS). They found that the associations between standing PNS activity (standing LnRMSSD) and other recovery markers (e.g. perceptual recovery, neuromuscular recovery markers) were stronger than supine. The associations were weak or inconsistent. Furthermore, individuals have shown different recovery time for HRV and neuromuscular measures. The authors recommend not to use HRV to infer for the recovery of other systems (i.e. neuromuscular). The study provides insight about individuality of recovery times and the associations between HRV and perceptive measures.
Formalioni, et al. ¹⁸	Level III	11 men with more than 6 months of strength training experience (aged 25±4 years)	Compared three conditions: i) 2 sets at 50% of 1 RM with 45 seconds of rest between sets, ii) 3 sets at 75% of 1 RM with 90 seconds of rest between sets and iii) 4 sets at 90% of 1 RM with 180 seconds of rest between sets of three exercises. The conditions were applied to three exercises: bench press, deadlift, and bent-over row to momentarily concentric failure. The experimental sessions were 5 to 7 days apart. The protocol monitored HRV in three moments: pre-warmup, immediately after the sessions and 24 hours after the sessions in a dorsal decubitus position. No difference was observed between the three conditions. In fact, the PNS activity was lower for all the sessions as well as for all time periods. It suggested that ANS responses to these three conditions were similar. The study was short term protocol (e.g

			experimental sessions were separated by 5 to 7 days), thus it is difficult to apply it in long term training prescription.
Heffernan, et al. ¹⁶	Level III	14 untrained men (aged 25 +/- 1.1 years, BMI 26.1 +/- 1.3)	Studied the effects of strength training on heart rate complexity (HRC) and HRV following a 6-week training period. They tracked HRV and HRC at baseline, after a 4-week time-control period, after 6 weeks of strength training and after 4 weeks of detraining. HRV data was collected supine after 15 minutes of rest. Untrained men were submitted to a 3 days per week two-way body part split with 5 exercises per session. The sessions lasted 60 minutes. For the first two weeks, the subjects performed 3 sets of 12 to 15 rep at 60-70% of 1 RM to fatigue. The rest intervals varied between 60 and 120 seconds. For the following 4 weeks, the subjects performed 3 sets of 8 to 12 rep at 70-80% of 1 RM to fatigue. The rest intervals varied between 60 and 120 seconds. They tracked PNS activity (LF, HF) and HRC. The main findings were that HRV was unchanged within the data collection points, whereas HRC was elevated following the intervention and back to baseline after the 4 weeks detraining period.
Holmes et al. ¹⁴	Level V	Collegiate male athlete (case study)	Tracked HRV over an 18 weeks periodized training program. The training frequency was set at 3 times per week. The sessions lasted from 60 to 90 minutes. There was at least 24 hours between the training sessions. An overview of the training periodization is available

			in Table 1. The authors provided full disclosure of the periodized program. They monitored PNS activity (RMSSD) every morning with smartphone pulse-wave finger sensor (PWFS). They monitored HRV in a seated position and took ultra-short 1 min recordings. They analyzed PNS activity in the form of weekly mean lnRMSSD ($\ln\text{RMSSD}_{\text{mean}}$) and the weekly coefficient of variation ($\ln\text{RMSSDCV}$). They evaluated the variations of HRV based on weekly workload. Increases and decreases in HRV based on volume variations have been observed. The relationships were not statistically significant. They calculated Pearson's correlation with $\ln\text{RMSSDCV}$ and total volume ($r=0.765$) as well as between weekly rate of perceived exertion (RPE) and total volume load ($r=0.853$). These results suggest that when the weekly workload was higher, PNS activity ($\ln\text{RMSSDCV}$) was lowered and that the rate of perceived exertion was also increased with higher workload. The case study design provides limited data and cannot be generalized to a larger population, however the length of the study allowed to observe the variations of HRV during a full 18 weeks periodized training cycle. The subjective data (i.e., RPE) also provided insight on fatigue with workload variations. The inclusion of HRV data and subjective
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			measures could provide additional information for kinesiologists to inform programming.
Holmes et al. ¹⁰	Level III	10 strength-trained individuals (8 men and 2 women), (aged 25.8 ± 6.8 years), (height: 173.4 ± 10.6 cm), (weight: 75.4 ± 9.9 kg), (bodyfat: $21.3 \pm 4.8\%$)	Assessed the acute changes in the ANS to different training volume loads in a cohort of 10 resistance strength-trained participants. The session duration varied based on volume. There were 3 different sessions: low volume (4 total sets), medium volume (8 total sets), and high volume (12 total sets). The sessions were at least 72 hours apart. The training intensity was set at 70% of 1 RM on three exercises: back squat, bench press, and bent-over rows. The rest intervals were 120s between sets and 180s between exercises. They monitored PNS activity (LnRMSSD) 10 minutes prior to the sessions and during the 30-minute window following the sessions. They monitored HRV in a seated position and analyzed it in 5-minute segments. The main finding was that the low-volume session led to a significantly higher PNS activity in the post-session window than both the medium and high-volume sessions, with no significant difference between the medium and high-volume sessions. This provides some information on the acute effects of increasing work sets on PNS activity.
Iellamo, et al. ¹⁷	Level III	9 weightlifters (5 men and 4 women), (aged 20-39 years), of weight class from	Assessed the changes in ANS with training load in a cohort of 9 weightlifters from the National Italian Team. The observations lasted a season culminating with the 2016 Olympics. The athletes trained 18

		48 kg to 70 kg, with at least 6 years of high-level competitions	times per week (3 times per day). The training regimen consisted of Olympic lifts (snatch, clean and jerk) and assistance exercises (powerlifts, squats, pulling exercises). The athletes performed 90 to 100 lifts per session with intensity varying from 70 to 100% of 1 RM. They monitored HRV laying supine for 10 minutes after 15 minutes of rest. They monitored PNS activity (HF band n.u.), SNS activity (LF band n.u.) as well as ANS balance (LF/HF). They observed a U-shaped curve with PNS activity (eg. an increase in PNS activation when volume was at its highest) and a bell-shaped curve with SNS activity and ANS balance (e.g. lowest SNS activity when volume was the highest, PNS dominance when volume was the highest). The authors suggested that the HRV responses may be sport specific. Other possible reasons for this inverted curve have not been discussed by the authors.
Kassiano et al. ¹¹	Level III	29 healthy participants (15 men and 14 women) (aged: 23.7 ± 3.7 years), (weight: 75.7 ± 15.0 kg), (height: 173.5 ± 9.6 cm), (BMI: 24.9 ± 2.9 kg/m ²), (training	Assessed the acute effects of four different training conditions in a randomized fashion on ANS activity. There were four total sessions with a washout week in between. All sessions consisted of one exercise, the parallel barbell back squat. The four conditions were: i) traditional ST not to failure (5 sets of 12 at 15 RM with 180s in between sets), ii) traditional ST to failure (4 sets of 15 at 15 RM with 200s in between sets), iii. inter-repetition rest (1 set of 60 repetitions

		experience: 6.8 ± 3.5 years).	with 10s of rest in between repetitions), and iv. rest-pause (blocks of repetitions to failure and 30s of rest between blocks until completion of 60 total repetitions). They monitored HRV with a Polar H10 chest strap. They monitored HRV in a seated position during 5 minutes pre-ST and 30 post-ST. They measured PNS indices (RMMSD, pNN50) and overall ANS activity (SDNN). The main finding was that condition iii (inter-repetition rest) led to no significant changes in ANS activity in the post-ST window and that condition iv (rest-pause) led to the most significant decrease in ANS activity in the post-ST window. The findings suggested that post-failure methods (rest-pause) induced more strain on the ANS. This provides some insight into the impact of different training systems or intensity techniques on ANS activity.
Mayo, et al. ¹²	Level III	17 healthy adults with at least 6 months of training experience (12 men, 5 women, aged 23 ± 2 years)	Compared three conditions in a randomized fashion across three lab training sessions: i) five sets of 8 repetitions (rep) with 3 minutes of rest between sets (7200 seconds), ii) ten sets of 4 rep with 80 seconds between sets (720 seconds) and iii) 40 sets of 1 rep with 18.5 seconds of rest between the repetitions (3200 seconds). All the sets had the same number of repetitions, were performed with a 10 RM load and total rest was equated. All their conditions were performed on a leg press machine. The three experimental sessions were at least 72 hours apart. They monitored PNS activity (RMSSD, HF) as well as ANS

			balance (LF band, LF/HF). The HRV was measured 10 minutes before the session and 20-40 minutes after the session, seated on the leg press machine. They found that the longest session (i.e. first session with 7200 seconds) led to a larger reduction in PNS activity (measured by RMSSD (root mean square of successive differences)) when compared to a quicker session (i.e. second session with 720 seconds). The training workload exposition was acute (one time), thus this is not a chronic or multiple weeks of training exposure. They did not measure HRV following a recovery period (e.g. 24-hour post-session).
Ramos-Campo, et al. ¹³	Level III	15 strength trained male athletes (aged 23.4 ± 2.4 year, 178.0 ± 7.6 cm, 78.2 ± 10.6 kg)	Studied the acute effects of training to failure or not to failure on sleep quality and HRV in 15 strength-trained male athletes. The protocol lasted four sessions at least 72 hours apart. The conditions were: i) 4 sets of 10 rep leading to failure and ii) 5 sets of 8(10) rep with 2 repetitions in reserve. The load was set at 75% 1 RM and the athletes rested 90 seconds between sets. The exercises performed were bench press and half-squat. They monitored sleep quality with an Actiwatch after each training session (laboratory sessions 1 and 3). They captured HRV data during sleep for 4 hours, starting 30 minutes after bedtime. They assessed subjective sleep quality with the Karolinska Sleep Diary. They found similar acute effects of the two conditions on HRV and sleep quality. This suggests that training to failure didn't lead to

			worse or better outcomes on ANS modulation. However, the subjects had a performance decrease 24h after the failure session, meaning they were not fully recovered. The authors hypothesized that the failure session may elicit factors such as muscle damage or biochemical markers that affect performance more than sleep. The subjects were highly trained athletes, therefore it is possible that the ANS recovered quickly from a single ST session.
Schneider, et al. ¹⁵	Level III	37 trained athletes (7 women, 12 men for the RT group) with at least 3 years of strength training experience.	They observed the HRV responses to functional overreaching. The protocol consisted in 6 different days of training. The protocol included lower-body exercises followed by a combination of upper-body, core, hamstring, and back exercises. An overview of the training parameters is disclosed in Table 1. After establishing HRV baseline for 4 days, the athletes trained 11 times in a 6 days microcycle (e.g. 2 times per day except for post-test day). They rested for 4 days afterwards. The training bouts lasted around 90 minutes. For 14 days, the athletes performed an orthostatic test each morning (7 min supine, 5 min seated). They monitored PNS activity (LnRMSSD and the LnRMSSD to R-R interval ratio (LnRMSSD/RR)) for the last 5 min of time spent supine and standing. LnRMSSD/RR was used to get additional information on HRV alterations associated with average heart rate. For the ST group, they observed an increase in HR and a

			decrease in supine HRV (e.g. decreased PNS activity), with a small effect size. No changes were noted for HR or HRV in the standing position. During the 4 days of recovery, supine HR was decreased and HRV was increased (e.g. increased PNS activity, decreased SNS activity), with a small effect size. The authors noted that all the links were weak or inconsistent. This provides insight on HRV responses to short-term ST overreaching in trained athletes.
Thamm, et al. ¹⁹	Level III	10 men with at least 6 months of strength training experience (aged 24 +/- 3.8 years)	Compared two strength loading protocols. Conditions were i) hypertrophy protocol with 5 sets of 10 rep at 80% of 1 RM with 2 minutes of rest between sets and ii) 15 sets of 1 rep at 100% of 1 RM with 3 minutes of rest between sets. Both conditions were performed on a leg press machine. HRV was monitored in 6 moments: pre-exercise, immediately after, 30 minutes, 1 hour, 24 hours and 48 hours post-intervention. The 2 sessions were 7 days apart. HRV data was collected supine for 10 minutes between 7 and 9 am. Orthostatic tests were also performed upon awakening. They measured PNS activity (RMSSD, HF band). They measured sympathetic activity with the LF band and the balance between PNS and SNS with the LF/HF ratio. They found that RMSSD was lowered in a similar fashion following both conditions (e.g. lower parasympathetic activity), but was back to baseline 30 minutes post-intervention. The LF band showed elevations

			for condition ii 48 hours post-intervention (e.g. elevated baroreflex activity during recovery). This means that RMSSD was not sensitive enough to monitor differences between the two conditions. The external validity was not applicable on the field, because the two conditions were performed on a single machine. This also provides insight about the impact of maximal effort lifts on baroreflex activity in the recovery phase.
Williams, et al. ⁷	Level IV	6 competitive Crossfit athletes: 3 men (aged 26 +/- 4 years), 1.83 +/- 0.6m, 88 +/- 2 kg; 3 women (aged 27 +/- 2 years), 1.67 +/- 0.10m, 67 +/- 9 kg	Evaluated HRV as a moderating factor in the workload-injury relationship on 6 competitive Crossfit athletes. For 16 weeks, they accounted for total workload and used the Overuse Injury Questionnaire along with smartphone photoplethysmography (PPG) PNS activity (RMSSD) data. The athletes collected ultra-short (1 min) measurements supine upon waking. The authors found that when the 7-day average for lnRMSSD was low, the risk of overuse injury was increased significantly. In addition, they found that high total workload was well-tolerated when the weekly RMSSD data was normal or high. Although this data is impossible to generalize to other populations, possibly being able to minimize risk of injury using HRV data provides further rationale to consider HRV data when planning training workload.

CHAPITRE 2

INTRODUCTION DE LA RECHERCHE

Le chapitre précédent a permis de mettre en évidence les recherches les plus pertinentes en lien avec le projet de maîtrise. Certaines études à long terme recensées, bien que peu nombreuses, ont permis de fournir les bases pour la construction du projet de recherche, qui se voulait une « *application terrain* » de plusieurs concepts soulevés par la revue de la littérature. Au total quatre articles ont été déterminants pour mon projet de recherche.

L'idée centrale du projet, soit d'utiliser la VFC comme facteur décisionnel pour déterminer la fréquence des entraînements, provient d'une étude de De Oliveira et al. (2019) qui s'est intéressée à la comparaison entre l'entraînement traditionnel (3 sessions par semaine) et l'entraînement à fréquence variable modulée par la VFC. Tel que décrit dans le chapitre précédent, les principaux résultats étaient que les deux groupes présentaient des profils similaires en termes de force et de composition corporelle. Une observation importante que j'ai fait était que le groupe expérimental (fréquence variable) avait complété les 20 séances d'entraînement en une plus courte période (5.1 semaines), ce qui suggérait que les participants avaient obtenu les mêmes gains que le groupe traditionnel, en moins de temps. Cette étude m'a amené à me poser la question suivante : « *Est-ce que ces résultats étaient explicables par des différences intergroupes ou par la façon de juger de l'état de récupération adéquat (basée sur une mesure basale et une mesure de seuil de VFC) ?* ». Également plusieurs questions persistent, mais compte tenu de ces résultats, l'intérêt de départ du projet était de comparer l'entraînement traditionnel à l'entraînement flexible sur une durée fixée à 6 semaines. Mon hypothèse de départ était que cumuler plus de volume en une période de temps plus courte mènerait à des gains supérieurs, principalement au niveau de la masse musculaire. Toutefois, compte tenu des difficultés rencontrées lors du recrutement des participants pour le projet de recherche, la formation d'un groupe contrôle n'a pas été possible et le projet a dû être amendé, avec la seule possibilité d'un groupe expérimental. La réalité du terrain au début du projet (contexte de la pandémie de Covid-19) a davantage orienté l'étude vers l'observation de l'efficacité de l'utilisation de la VFC dans

un cadre écologique de suivi à distance, avec l'objectif d'obtenir des données préliminaires sur l'utilisation de la VFC comme outil de suivi de la récupération.

À priori, l'étude de Heffernan et al. (2007) citée dans la revue de la littérature fournissait des bases intéressantes quant à l'organisation de l'entraînement traditionnel pendant 6 semaines. Toutefois, une observation importante était que l'étude ne proposait que quatre points de collecte de données pour la VFC sur l'ensemble des 6 semaines. Ce qui m'a amené à me poser la question : « *Les résultats de VFC auraient-ils pu être différents avec une collecte journalière de données ?* ». Ce questionnement a conduit à l'adhésion à cette seconde méthode. De plus, à posteriori, il fut observé que l'étude de Heffernan et al. (2007) proposait une charge de travail similaire à celle prescrite dans notre protocole, en recourant à l'entraînement traditionnel tout en observant les changements de la VFC, ce qui permettait, en quelque sorte, de comparer leurs résultats aux nôtres, car malgré des différences méthodologiques, les charges de travail étaient jugées relativement équivalentes.

L'étude de cas de Holmes et al. (2018) a mis en évidence une dimension qui a retenu l'attention en vue de la création du protocole d'entraînement, à savoir l'observation des changements de la VFC à moyen et long terme dans un contexte de charge de travail croissante. « *Est-ce que la VFC serait sensible à l'accumulation de la charge de travail pendant la période de collecte ?* ». Une nouvelle question s'ajoutait. Cette étude mettait également de l'avant le principe écologique de suivi hors-laboratoire qui, pour moi, collait bien à la réalité du terrain. Qui plus est, l'étude abordait l'idée de traiter la VFC sous forme de moyenne hebdomadaire et de mesurer la charge de travail sous forme de tonnage, des idées que j'ai retenues en vue du projet.

Finalement, l'étude observationnelle de Williams et al. (2017), auprès de 6 athlètes compétitifs de Crossfit, qui s'était intéressée à la VFC, à la charge de travail et au risque de blessure de surutilisation, soulevait des associations intéressantes entre la charge de travail, la diminution de la VFC et le risque de blessure de surutilisation. Ces observations venaient renforcer l'idée initiale d'utiliser une méthode de suivi informée par des données objectives en vue d'améliorer les méthodes de suivi et de mieux outiller les physiologistes de l'exercice

et entraîneurs afin qu'ils puissent prendre des décisions éclairées. Tout cela s'avérait pertinent dans le but de maximiser les gains en entraînement en réduisant le risque d'effets indésirables dans le contexte de suivis à distance. La revue de littérature a donc fourni quelques pistes pour structurer l'intervention, mais a tout autant mené à un ensemble de questions étant donné que, en somme, peu d'études ont été faites auprès de populations similaires et les interventions étaient hétérogènes.

Donc en se basant sur les manques présents dans la littérature décrits de manière plus exhaustive au chapitre précédent, notamment le manque de connaissances sur les bonnes pratiques de collecte de la VFC dans le contexte de l'entraînement en musculation, le manque de considérations holistiques dans l'analyse de données, le faible volume d'études à long terme reliant VFC et entraînement en musculation, et le besoin d'un outil plus efficace pour monitorer ce type d'entraînement, l'objectif principal du projet était de fournir des données préliminaires pour le développement de l'outil dans le contexte de suivis à distance de l'entraînement en musculation. Les objectifs secondaires étaient 1) d'évaluer l'adhésion au protocole d'entraînement à distance pendant 6 semaines ; 2) d'évaluer si un tel protocole d'entraînement musculaire utilisant la VFC pour moduler la fréquence d'entraînement pouvait mener à des gains au niveau de la performance ou de la composition corporelle ; et 3) d'étudier les relations entre la VFC et des données subjectives de récupération fournies par les participants.

CHAPITRE 3

ÉTUDE D'EFFICACITÉ

Jean-Philippe Morin, Andrée-Anne Parent, Mathieu Tremblay. Titre : « *Individualized Heart Rate Variability on a strength 6-week training program. A remote-coaching effectiveness study* ». Manuscrit publié dans: « *International Journal of Sports Science & Coaching* » (DOI : 10.1177/17479541261436950).

Résumé

Les physiologistes de l'exercice et les entraîneurs prescrivent l'entraînement de la force à diverses populations avec des buts individuels. L'accompagnement basé sur les données est crucial avec la hausse des suivis à distance, particulièrement dans les régions rurales, pour pallier le manque de supervision directe. La variabilité de la fréquence cardiaque (VFC) est devenue un outil utile pour mesurer les effets du stress de l'entraînement sur le système nerveux autonome et est facilement accessible avec des outils portables. Le but de cette étude était d'évaluer l'efficacité d'utiliser la VFC pour ajuster l'entraînement de la force dans un contexte d'entraînement à distance mené avec un groupe de participants entraînés récréatifs. Les participants ont complété un programme d'entraînement de la force de 6 semaines avec des tests pré- et post en laboratoire (force, composition corporelle, tension artérielle). La VFC a été mesurée sur une base journalière par les participants, et une valeur seuil de VFC a été calculée pour déterminer s'ils devaient s'entraîner chaque jour. Les données d'entraînement et un questionnaire journalier ont également été complétés et soumis au chercheur principal. Les principaux résultats ont montré que l'adhésion au protocole était élevée si l'on compare à d'autres interventions dans la population générale et que le protocole a mené à des gains de force significatifs sans avoir d'impact significatif sur la modulation du système nerveux autonome. Cette étude contribue à fournir des évidences préliminaires pour supporter l'efficacité d'un programme d'entraînement de la force guidé par la VFC pour l'entraînement à distance.

Abstract

Exercise physiologists and coaches prescribe strength training to diverse populations with individual goals. Data-driven coaching is especially crucial with the rise of remote coaching, particularly in rural areas, to compensate for lack of direct supervision. Heart rate variability (HRV) has become a useful tool for measuring the effects of training stress on the autonomic nervous system and is easily accessible via wearables. The purpose of this study was to assess the effectiveness of using HRV to adjust strength training frequency in a remote coaching setting led by a group of recreationally trained participants. The participants completed a 6-week strength training program with pre- and post-lab testing (strength, body composition, blood pressure). HRV was collected daily by the participants, and an HRV threshold was calculated to determine whether they should train each day. Training data and a daily questionnaire were also completed and submitted to the leading researcher. The main findings showed that adherence to the protocol was high compared to other interventions in the general population and that the protocol led to significant strength gains without significantly impacting autonomic modulation. This study contributes to preliminary evidence supporting the effectiveness of HRV-guided strength training in remote settings.

Keywords

Training tool, Recovery monitoring, Training workload, Remote coaching, Resistance training.

3.1 INTRODUCTION

Exercise physiologists and coaches prescribe resistance- or strength-training (ST) programs to diverse populations seeking improvements in health, performance, and activities of daily living. Long-term benefits—from increases in lean mass and bone density to better metabolic and psychological health—depend on delivering an adequate workload while allowing sufficient recovery between sessions.¹ The balance between workload and recovery is difficult to achieve in practice: excessive loading or inadequate rest can lead to suboptimal results or unwanted effects such as injuries, loss of motivation for exercising, and physical or mental fatigue, and, in extreme cases, precipitate adverse conditions such as exertional rhabdomyolysis.^{2,3} Recovery capacity varies widely among individuals;⁴ therefore, coaches require objective tools to monitor the balance between training workload and recovery. Chen et al.⁴ demonstrated that parasympathetic nervous system activity closely mirrors individual recovery capacity following exercise, highlighting that recovery varies substantially between athletes due to autonomic responsiveness, accumulated fatigue, and training load—therefore requiring coaches to rely on objective physiological tools (e.g., heart rate variability (HRV) monitoring) rather than subjective perception to accurately individualize training and optimize adaptation. Therefore, recovery capacity is profoundly individualized, varying widely due to physiological factors such as genetics and training history, as well as lifestyle and psychological factors such as sleep quality and stress levels.⁵⁻⁷ This inherent variability means that coaches cannot rely on generalized protocols or subjective assessments alone, as what promotes recovery for one athlete might lead to overtraining in another.⁸ Consequently, coaches require objective tools, such as HRV monitoring, biological tests (salivary cortisol, immunoglobulin A, testosterone...), psychological and social monitoring and performance tests (isokinetic strength testing, jump test, grip strength, agility test...), to monitor the balance between training workload and individual recovery, thereby preventing overtraining and optimizing adaptation and performance.^{5,9-11} However, some testing can be more expensive or difficult to use, such as biological sample testing compared to others like the HRV.

Heart rate variability (HRV)—an index of autonomic nervous system activity—has emerged as a promising measurement. HRV is an indirect measure of the autonomous nervous system's (ANS) activity, which regulates various automatic processes throughout the body (e.g., blood flow, breathing, digestion, and temperature regulation). In the context of ST, previous studies have shown an acute decrease in HRV (higher sympathetic activity, lower parasympathetic activity); following adequate recovery, HRV increased, showing an increase in parasympathetic activity and a decrease in sympathetic activity, respectively. Furthermore, acute ST sessions typically suppress parasympathetic tone and reduce HRV; subsequent restoration or “rebound” signals that the athlete recovered.^{3,12} Parasympathetic responsiveness also appears to be sensitive to training volume, suggesting that HRV could guide day-to-day decisions about session frequency or load. While HRV-guided prescriptions are gaining popularity in endurance sports,¹³ only a few studies have explored this approach in ST. Notably, De Oliveira et al.¹⁴ demonstrated that adjusting session frequency to daily HRV yielded comparable strength and hypertrophy in fewer sessions than a fixed-frequency plan. However, their work was conducted face-to-face and used a fixed number of sessions rather than a fixed intervention duration.

The rationale for remote, data-informed coaching is particularly strong in rural and geographically dispersed regions, where limited access to qualified exercise professionals and training facilities constrains structured supervision and long-term adherence. Rural populations report reduced access to exercise services and greater logistical barriers, including travel burden and limited facility availability, which are associated with lower participation and higher adherence rates in structured programs.¹⁵⁻¹⁸ Telehealth and remote supervision models have emerged as viable strategies to mitigate these disparities, demonstrating comparable effectiveness to in-person interventions in several rehabilitation and chronic disease contexts.¹⁹⁻²⁰ Parallel advances in wearable sensor technology and mobile health platforms now enable continuous, non-invasive physiological monitoring outside laboratory settings, increasing the feasibility of scalable remote coaching systems.²¹⁻²³ Within this technological framework, heart rate variability (HRV) provides a validated marker of autonomic nervous system activity and recovery capacity, reflecting the dynamic

balance between sympathetic stress and parasympathetic restoration following training stimuli.^{24,25} As explained previously, individualized recovery capacity is known to vary substantially between and within individuals due to accumulated fatigue, sleep quality, psychosocial stress, and training load.²⁶⁻²⁸ Without objective monitoring, coaches relying solely on subjective feedback risk misaligning training frequency with physiological readiness, potentially impairing adaptation or increasing injury risk. Integrating HRV monitoring into remote coaching models, allows practitioners to individualize training frequency and adjust load based on objective recovery status, thereby partially compensating for the absence of direct supervision and supporting adherence through tailored, data-driven feedback mechanisms. Therefore, incorporating HRV monitoring into a remote program could help fill the supervisory gap by customizing the frequency to individualize training and ensure adequate supervision and support, based on observations of a sedentary population.²⁹

The main objective of this study was to evaluate the effectiveness of an HRV-based, individualized frequency ST program implemented through remote coaching over 6 weeks. We hypothesize that integrating daily HRV monitoring into our 6-week remote ST program, will lead to higher participant adherence compared to a program without direct supervision, as reported by Yuki Arikawa et al.,¹⁵ by tailoring training frequency to each participant's actual recovery status, we believe the program will be more effective and better aligned with their perceived energy levels and recovery. This alignment could provide a form of supervision and support needed without direct supervision.²⁹ The secondary objective was to investigate the effect of an HRV-based program on gains in muscle mass and strength for squat and bench exercises over a 6-week period. We also aim to document digital tools and protocols for remote coaches in rural regions, where coaches must support clients across large geographic areas and cannot provide constant in-person supervision.³⁰

3.2 METHODS

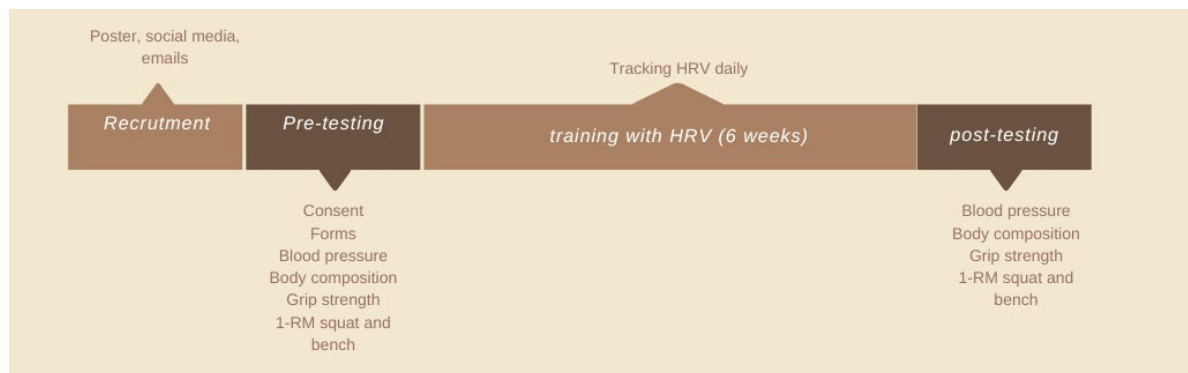
3.2.1 Participants

This study used 9 participants (7 males and 2 females) with a mean age of 29.7 ± 8.8 years (estimated squat 1RM: 100.2 ± 49.7 kg (220.9 ± 109.5 lbs.), estimated bench press 1RM: 77.6 ± 39.9 kg (171.1 ± 88.0 lbs.)) Participants were recruited through voluntary response to advertisements (posters, email, and social media), constituting a non-probabilistic convenience sample. Participants were excluded if they did not have at least 24 months of reported strength training experience, had limitations to train such as chronic health or psychosocial issues (e.g., diabetes, cardiovascular disease, musculoskeletal issues, depression, anxiety disorders, alcoholism), used anabolic steroids or anabolic substances in the past 24 months, had symptoms of overtraining or have had rhabdomyolysis in the past or had any prescription medication that could affect HRV. Menstrual cycle details and oral contraceptive use were not included in the demographic data questionnaire. All participants were informed verbally and in writing of all procedures, risks, benefits, and their rights during the study before signing a consent form approved by the Research Human Ethics Committee of Université du Québec à Rimouski (CER-122-995).

3.2.2 Study Design

This free-living single-group interventional study followed the study design illustrated in Figure 5.

Figure 5. Study design.



3.2.3 Pre- and post-testing

At the pre-test appointment, participants received detailed instructions on the testing procedures, the detraining period, methods for collecting heart rate variability (HRV), training data collection protocols, and how to complete an online self-assessment questionnaire. Following this briefing, informed consent was obtained, and participants completed the Get Active Questionnaire³¹ and the Nordic musculoskeletal Questionnaire³² as screening tools.

Assessments were conducted in the morning or early afternoon in a temperature-controlled environment. Both pre- and post-testing included measurements of resting blood pressure, seated grip strength, body composition via bioimpedance and ultrasound, and one-repetition maximum (1RM) estimations for barbell squats and bench press.

Resting blood pressure was measured first to ensure participant's safety. Following with the body composition assessment using the bioimpedance assessment, verbal instructions were provided according to the manufacturer's protocol (Inbody770, South Korea).³³ The body composition analysis also included an ultrasound scan using the BodyMetrix system (IntelaMetrix, Livermore, USA).³⁴ The ultrasound algorithm was based on the right side of the seven-site skinfold method of Jackson & Pollock (i.e., triceps, biceps, subscapularis, suprailiac, abdomen, thigh, and calf)³⁴. This measurement was performed by the same staff who received company training.

For strength evaluation, grip strength was assessed with participants seated, their arms at their sides, and their elbows flexed at 90 degrees using a hand dynamometer (Jamar, USA). Participants maintained a neutral wrist position throughout the test. Three trials were conducted for each hand, and the average of the three trials was calculated. Furthermore, a 1-RM test was performed and was estimated for both barbell squat and bench press using a six-repetition maximum (6 RM) test. Foot position during squats was not standardized, but the distance between participants' heels was recorded to ensure consistency across the pre- and post-tests. A squat wedge was used, and squats were required to reach minimum depth consistent with International Powerlifting Federation (IPF) technical rules.³⁵ Spotting was provided by the research team, to ensure that the anterosuperior iliac crest dropped below the top of the knee. For the bench press, the procedure followed the American Council on Exercise (ACE) guidelines.³⁶ Two submaximal warm-up sets (initial load determined by participants) were performed for each exercise, followed by incremental increases in weight (determined by participants between trials). Participants were allowed four minutes of rest between trials. Testing was conducted to assess volitional failure, defined as the participant's decision that they could not perform more than 6 repetitions. In some cases, participants were unable to complete the last repetition, indicating a momentary failure. The number of attempts was between 2-4 after the warm-up. Final 1-RM estimations were calculated using the NSCA 1-RM prediction chart.³⁷ The NSCA prediction chart was based on previously published regression equations derived from empirical strength testing datasets, primarily those reported by Brzycki³⁸ and Epley³⁹, which modelled the relationship between load and number of repetitions performed to failure.⁴⁰ Minimum squat depth was standardized to ensure consistency across participants. A repetition was considered valid when the iliac crest descended below the superior border of the patella (i.e., achieving at least parallel squat depth). Depth was visually monitored in real time by a trained member of the research team positioned laterally to the participant. All assessors were trained prior to data collection to ensure consistency in depth determination. If a repetition did not meet the minimum depth criteria, participants were verbally cued to adjust subsequent repetitions.

3.2.4 Heart Rate Variability baseline

After initial testing, participants were asked to refrain from intense exercise for 5 days before the 6 weeks of continuous ST. HRV data was collected every morning to establish a baseline. The participants were required to collect HRV for 10 minutes under the same conditions (upon waking up, after urinating, in the supine position in bed, and before ingesting food or drink) using a heart rate monitor (H10, Polar, Fi). The mean and standard deviation for the 5 days were calculated. The baseline was defined as the average of the five detraining days. The HRV floor value was calculated as the baseline value minus 1 standard deviation.

3.2.5 Strength-training program

After baseline testing, participants underwent a 6-week ST program. The program consisted of a rotation between 6 sessions using a push-pull-legs split (supplemental material is available for details). The training program consisted of 3-4 sets of 5 exercises per session, with 6-10 repetitions per exercise. The intensity was set at 1-3 repetitions in reserve, so the last working sets were carried close to momentary failure. The rest periods between sets were 90 to 120 seconds. The sessions started with compound exercises and followed by isolation movements. The participants were instructed to train on a flexible schedule determined by their daily HRV. The program was available on the remote coaching tool TrainHeroic (Mobile application software, USA). The participants had access to detailed daily sessions on the mobile application, which included tutorial videos for each exercise. The participants were instructed to refrain from intense exercise outside of the prescribed training protocol for the duration of the experiment.

3.2.6 Participants' Self-Reported Measures and HRV during training

The HRV data was recorded on each participant's mobile phone using an application (Heart Rate Variability Logger by A.S.M.A. B.V.). Each morning, participants emailed the data to the team for analysis using the export function. HRV data was analyzed using computer software (KubiosHRV V 2.2, Finland), and ectopic beats were removed using the same software. A 5-minute sample of the clearest signal was used for analysis. The root-mean square of successive differences between normal heartbeats (RMSSD) was used to determine training status. It was communicated to the participant, indicating whether to train or not that day. If the RMSSD for the day was below the RMSSD at baseline minus one standard deviation (HRV floor), the participant was instructed not to train that day.¹⁴

3.2.7 Data analysis

The training conditions were reported and numerically coded as such: 1. Could not train, did not train, 2. Could train, did not train, 3. Could train and trained, 4. Could not train, but trained, and 5. HRV data missing. Two groups were formed from this adherence data: : more adherent participants were those who respected training conditions 1 and 3 at least 75% of the time and had omitted HRV tracking no more than 25% of the time (condition 5). At the same time, less adherent participants did not meet these criteria. The term 'adherence' was used in this paper to describe a participant's active choice to use the prescribed intervention for their well-being in an ecological environment.⁴¹

The HRV variables analyzed were the RMSSD (HRV) and HRV floor to determine the training days. The RMSSD difference daily compared to baseline (HRVdiff), the average RMSSD per week (HRVavg), the ratio of HRVdiff to HRV floor (HRV floor ratio), and the average of HRV floor ratio were used to observe fluctuations during the 6-week training program. Also, the square root of the sum of the square roots of the different previous variables was calculated and divided by the number of variables obtained during the week (RMS) to assess variance.

Statistical testing was performed using JASP v.0.18.3 (Apple Silicon, USA) software. After visual inspection, the Shapiro-Wilk test was used to test the normality. Paired T-tests were performed to analyze the results of pre-post testing. RMANOVA (Friedman tests) and Conover post hoc testing were performed for the HRV and training load variables to evaluate changes from week to week. Compliance was added as a moderating factor. The alpha criterion for significance was set at 0.05. Cohen's *d*-effect sizes were also reported to observe the magnitude of mean differences (small = 0.2; medium = 0.5; large = 0.8; very large = 1.3).⁴²

3.2.8 Training quantification

The training volume load (TVL) was calculated as tonnage (number of repetitions multiplied by the load (in lb)) extracted from the training mobile application. An average was calculated each week to minimize daily fluctuations, and summation of these TVLs (total TVL) was performed to evaluate workload changes between weeks. The variance in training volume for each week was calculated using the square root of the summation of the total volume load (TVL) of the week, divided by the number of training sessions during the week (RMS TVL).

3.3 RESULTS

Eight participants completed the 6-week protocol and underwent both pre- and post-testing. One participant requested to drop out before the final week of the experiment. The participants completed 20.6 ± 5.5 sessions according to training logs.

3.3.1 Pre and post-testing

The pre- and post-testing data are presented in Table 3. The comparison of pre- and post-for systolic ($t(6) = 1.628$, $p = .155$, $d = 0.615$) and diastolic blood pressure ($t(6) = 2.018$, $p = .090$, $d = 0.763$) was insignificant. For both variables, pre-data was missing for 1 participant. **Body composition:** Pre-post body weight comparisons were insignificant ($t(7) =$

-1.790, $p = .117$, $d = -0.63$). Pre-post comparisons for body fat percentage were significantly higher at post-testing for bioimpedance ($t(7) = -2.398$, $p = .048$, $d = -0.85$) and ultrasound ($t(7) = -6.621$, $p < .001$, $d = -2.34$). Pre-post changes for skeletal muscle mass from the bioimpedance were not significant ($t(7) = -0.852$, $p = .422$, $d = -0.30$). Pre-post muscle mass from ultrasound was not significant ($t(7) = 0.504$, $p = .630$, $d = 0.18$). **Strength:** Pre-post comparisons for grip strength (average of both hands) were not significantly different ($t(6) = -0.278$, $p = .790$, $d = -0.11$). Pre-post comparisons were not significantly different for estimated bench press 1 RM ($t(7) = 0.208$, $p = .841$, $d = 0.07$). Pre-post comparisons were significant for the estimated 1 RM squat ($t(7) = -3.999$, $p = .005$, $d = -1.41$).

3.3.2 Heart rate variability

The different HRV variables are presented by week in Table 4. Average HRV per week showed no significant changes ($\chi^2(5) = 8.43$, $p = .134$). HRV floor ratio changes were not significant ($\chi^2(5) = 8.43$, $p = .134$). Root-mean square HRV (RMS HRV) was not significant ($\chi^2(5) = 7.36$, $p = .195$). Pre-post comparisons for root mean square difference HRV (RMSD HRV) were not significant ($\chi^2(5) = 7.429$, $p = .191$).

Table 3. Fitness characteristics from pre- and post-testing.

Tests	Adherent group (n=4)		Less adherent group (n=4)		All (n=8)	
	Pre	post	pre	post	pre	post
<u>Blood pressure</u>						
(mmHg)						
Systolic	131.67±8.33	130.0±5.57	132.25±7.59	120.75±16.5	132±7.2	122±14.33
Dyastolic	82.67±10.2	71.00±11.0	84.25±7.37	79.0±14.2	83.57±7.9	75±11.8
<u>Bioimpedance</u>						
% body fat	14.1±8.43	16.1±7.22	19.35±13.95	21.8±16.33	16.73±11.03	18.95±12.08*
muscle mass (kg)	42.15±3.29	42.08±3.23	30.67±5.77	31.38±6.78	36.41±7.5	36.72±7.54
<u>Ultrasound</u>						
% body fat	12.7±5.29	14.33±4.87	17.35±11.63	18.85±12.3	15.03±8.7	16.59±8.99*
% muscle mass	20.5±1.43	20.4±1.53	15.95±2.04	15.88±2.48	18.22±2.93	18.14±3.08
<u>Grip strength (kg)</u>						
Average	58.22±22.33	61.32±16.51	38.63±11.02	37.25±10.37	45.23±16.68	45.68±14.87
<u>1-RMest Squat (lb)</u>						
Absolute	265.78±101.89	290.25±102.53	141.17±69.44	151.48±68.19	203.47±104.65	220.87±109.5*
<u>1-RMest Bench (lb)</u>						
Absolute	220.58±87.18	231.04±84.78	126.7±77.0	111.22±35.99	173.64±91.2	171.13±87.96

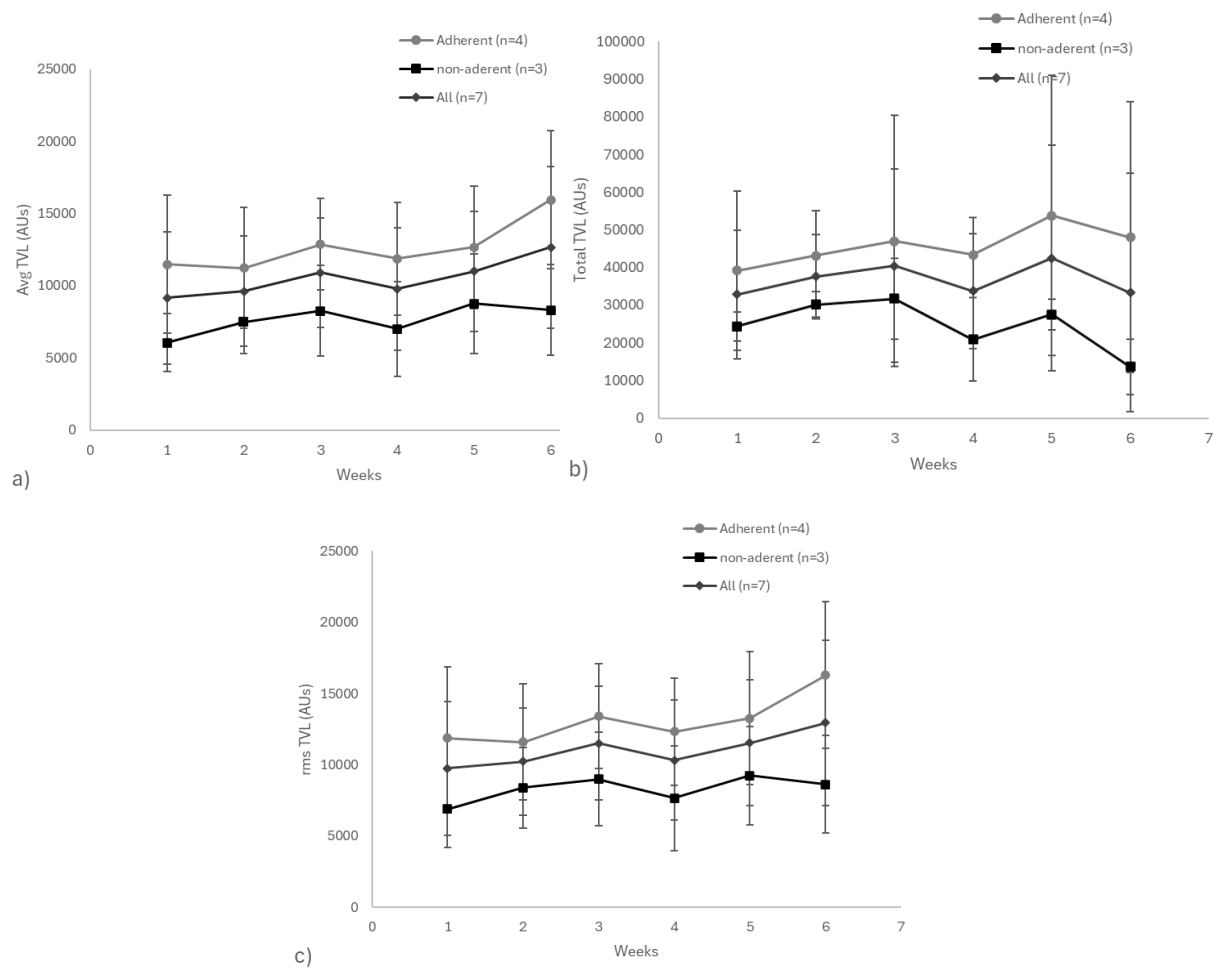
Note. Values presented as mean ± SD, * significant difference compared to pre-test ($p<0.05$), t: significant difference between groups; 1-RMest: 1-RM estimation.

Table 4. Heart rate variability by week during the 6-week training program.

HRV variables		Adherent group (n=8)	Less adherent group (n=4)	All (n=8)
<u>Average</u> <u>HRV</u>	Week 1	83.11±27.6	65.1±27.6	74.11±31.77
	Week 2	82.34±39.88	66.29±26.91	74.32±32.64
	Week 3	85.42±33.94	67.21±26.17	76.31±29.7
	Week 4	85.82±37.58	56.1±33.83	70.96±36.72
	Week 5	82.19±29.56	58.34±31.73	70.27±31.12
	Week 6	77.45±33.4	59.22±26.95	68.34±10.51
<u>HRV</u> <u>floor ratio</u>	Week 1	-0.030±0.114	0.124±0.388	0.047±0.098
	Week 2	-0.042±0.175	0.203±0.518	0.08±0.381
	Week 3	0.036±0.186	0.231±0.566	0.133±0.403
	Week 4	0.011±0.128	-0.124±0.220	-0.056±0.182
	Week 5	0.042±0.322	0.025±0.469	0.033±0.373
	Week 6	-0.041±0.275	0.065±0.504	0.012±0.380
<u>RMS</u> <u>HRV</u>	Week 1	84.88±37.75	67.63±25.57	76.26±31.24
	Week 2	85.08±40.2	69.6±25.6	77.34±32.28
	Week 3	88.77±34.84	71.41±25.96	80.09±29.92
	Week 4	89.38±38.77	58.2±33.35	73.79±37.4
	Week 5	85.22±29.03	61.69±30.27	73.46±30.2
	Week 6	81.36±31.44	62.41±25.42	71.88±28.34

Note. Values presented as mean ± SD, * significant difference between weeks ($p < 0.05$), t: significant difference between g; HRV floor ratio: (daily HRV/HRV floor value (baseline HRV-SD)); RMS HRV: root-mean square of HRV.

Figure 6. Training volume load.



Note. Training volume load variable for each week: a) Average TVL for both group together and separately per week, b) Total TVL both group together and separately per week, c) The root-mean-square of TVL (RMS TVL) for both group and separately per week. AU means for arbitrary units

The TVL is illustrated in Figure 2. Average TVL per week almost reached significance ($\chi^2(5) = 10.67, p = .058$) (fig 2.a). Total TVL per week changes were not significant ($\chi^2(5) = 4.39, p = .495$). Total TVL increased from weeks 1 through 3 and decreased in week 4. This decrease was followed by an increase in week 5 and a decrease in the last week (fig 2.b). Repeated measures ANOVA showed no effect of compliance for average TVL ($F(5, 1) = 1.16, p = .355$) and total TVL ($F(5, 1) = 0.541, p = 0.744$) for weeks 1 through 6 (fig 2b). The root-mean-square of total weekly TVL (RMS TVL) was significant ($\chi^2(5) = 12.88, p = .025$). Conover's post hoc test was run to observe differences between specific weeks. The plot showed a linear increase in total weekly TVL variance for weeks 4 to 6 (2c).

3.3.3 Adherence

Overall, participants adhered to the training conditions on average 78 % of the time. Approximately 13 % of the time, participants did not train when instructed, whereas 5 % of the time, they trained when instructed to rest. 4 % of the time, the research team was unable to determine the participants' status due to missing data.

3.4 DISCUSSION

This study aimed to evaluate the effectiveness of a 6-week HRV-based, remotely supervised strength-training (ST) program with individualized frequency. The main hypothesis was that integrating daily HRV monitoring would enhance adherence to the training frequency by optimizing the alignment between training demands and recovery status. This remote framework was designed to address known adherence challenges in unsupervised programs¹⁵ by offering a personalized structure that can mimic supervision through objective recovery monitoring.²⁹ The average adherence (78 %) to the protocol was superior to most unsupervised training interventions within the general population;^{16,29} in sedentary populations, a similar intervention using a mobile application and training guided by HRV by Casanova-Lizón et al.²⁹ had an average compliance of 70.5 %, which is almost

identical to what we observed. A secondary aim was to explore the effects of this intervention on muscle mass and strength (bench press and squat). Our hypothesis that muscle mass and strength would increase for adherent people compared to nonadherent people was partially confirmed. The 6-week intervention significantly increased the estimated 1-RM squat for all participants. However, muscle mass and 1-RM bench press estimates did not differ significantly after the intervention, whereas body fat measurements increased significantly. The observed significant increase in body fat percentage should be interpreted cautiously. Although statistically significant, this magnitude of change approaches the known reliability limits of the assessment devices used.³³⁻³⁴ Therefore, part of this variation may reflect measurement variability rather than a true physiological increase in adiposity. Also, it is important to note that 1-RM values were estimated from 6-RM testing, which carries a reported prediction error of approximately 0.03-0.05 % for the squat and approximately 1-4 % for the bench press.⁴³ Therefore, although the magnitude of change suggests a possible physiological adaptation or not, part of the improvement or maintenance may reflect methodological variability. However, the findings could guide the creation of remote coaching tools suitable for rural areas where in-person coaching is limited.

3.4.1 Adherence to Protocol

Adherence was assessed using daily HRV data submissions and compliance with personalized training prescriptions. Participants who submitted HRV data and followed the training prescriptions at least 75 % of the time were considered more adherent. Using this standard, half of the participants were classified as more adherent for analysis, with an average adherence to the training conditions of 78 %. Literature indicates notable differences in adherence between supervised and unsupervised training. Supervised programs show higher adherence rates, with 95 % adherence for supervised versus 65 % for non-supervised programs in Arikawa et al.¹⁵ and 76 % for the supervised ST program in Davis et al.⁴⁴ among women with obesity. Our study more closely aligns with an HRV-guided intervention by Casanova-Lizón et al.²⁹ in a sedentary population. We recorded an average adherence rate of 78 % and a dropout rate of 11 % (e.g., one participant withdrew before the end of data

collection). These findings align with their observed average adherence rate of 71 %. This suggests that HRV tracking and flexible frequency may have enhanced motivation and accountability. To our knowledge, very few studies explored adherence to remote ST interventions in recreationally trained individuals, making it challenging to compare adherence to the protocol with that of equivalent interventions and populations. It is also noteworthy that the definition of adherence may vary in supervised studies.

3.4.2 Effects on Physical Fitness

The 6-week HRV-based, remotely supervised ST program with an individualized frequency significantly improved estimated squat 1RM but not bench press strength. This outcome corroborates findings from De Oliveira et al.¹⁴, who also observed significant improvements in lower body strength in a similar HRV-based intervention. Overall, the training volume of their intervention was superior to ours (8 exercises versus 5). They observed a significant increase in leg extension and estimated 1RM following 20 sessions of ST intervention modulated by HRV, with similar strength gains observed in the traditional ST group (3 sessions per week). The absence of bench press strength gains compared to the De Oliveira et al.¹⁵ may be attributed to participants' training experience—many had more than two years of ST before the intervention—and the well-established principle that strength gains are more rapid in novices due to neural adaptations.⁴⁵ The mechanisms explaining strength gains are still being studied, but include motor learning (more efficient contraction of agonist muscles), increased excitability of motor units, and reduced cortical inhibition.⁴⁵ Moreover, it is also still possible that, for strength gain outcomes, direct supervision by professionals remains superior.²⁹ Additionally, the 6-week intervention period may have been too short to elicit visible hypertrophy, especially in trained individuals.⁴⁶ Our study also used moderate loads (6-10 repetitions per set). According to the general literature, high loads tend to be slightly more effective than moderate loads for strength outcomes, in line with the specificity principle. However, significant strength gains are also seen with moderate loads.⁴⁷ Muscle growth is possible with light, moderate, or high loads, if sets are performed close to failure.⁴⁸⁻⁵⁰ A similar outcome was found in a 6-week study conducted on 14 untrained men

by Heffernan et al.,⁵¹ which used a similar training frequency and weekly training volume. Our participants underwent training in 15 to 29 sessions over a 6-week period, averaging 20.6 sessions per participant. The study by Heffernan et al.⁵¹ involved a 3-session-per-week supervised ST intervention with three sets of 5 exercises (8 to 15 repetitions) aimed at momentarily fatiguing the muscles. Our intervention involved similar volumes, consisting of 3 to 4 sets of 5 different exercises (6 to 10 repetitions) with increasing proximity to failure. Given the flexible training frequency, it is plausible that some participants trained too little to produce adaptations over 6 weeks, as progressive overload is necessary to prevent stagnation and training volume is a key factor in muscle gains.^{52,53} This could be because, in trained lifters, training history (defined by their usual training volume) influences hypertrophy outcomes, meaning the protocol might not have been a significant enough increase in workload from their typical routine to induce muscle adaptations over 6 weeks.⁵⁴ There can also be variance in the definition of trained participants across studies, with some studies considering 6 months of ST experience sufficient.⁴⁶ Our participants reported varying levels of training experience, with one participant reporting 15 years or more of continuous ST experience. Other factors, such as genetics and lifestyle, can influence the rate of muscle growth. Our results differed from those of a study by De Oliveira et al.^{#4}, which showed a significant increase in quadriceps cross-sectional area in untrained participants after 20 training sessions. This was further compounded by the lack of control over caloric intake, which could have contributed to the observed increase in fat mass. Participants may have been in a caloric surplus, as ST without dietary control has a limited effect on reducing fat mass.⁵⁵

3.4.3 Effect of training parameters on HRV

Using daily HRV to guide training decisions offered an objective "green-light/amber-light" cue that replaced in-person supervision and likely supported the high adherence observed: trainees could skip a session without guilt when HRV indicated incomplete recovery, yet they also had clear permission to train once their autonomic status improved. This flexible approach mirrors the design of De Oliveira et al.¹⁴ while adapting it to a real-

world six-week setting. It seems to have stabilized parasympathetic tone, with weekly HRV metrics remaining consistent despite increasing ST volume and proximity to failure, thereby reducing fatigue and supporting proper recovery. We monitored workload primarily through two metrics: tonnage, recorded via training journals on the mobile app, and repetitions in reserve (perceived intensity by participants). We expected tonnage to change significantly during the six-week period, reflecting increased training intensity. Additionally, we hypothesized that workload increases would result in a significant decrease in HRV over time, because medium to high volumes are reported to cause a larger short-term reduction in HRV.⁵⁶ The average change in training volume nearly reached significance ($p = .058$), though total weekly volume did not ($p = .495$), possibly due to significant variance in training load ($p = .025$). Despite non-significant changes in total weekly training load, our data suggest that autoregulated intensity using repetitions in reserve effectively helped recreationally trained participants increase effort, resulting in significant strength gains. This aligns with existing research, which shows that autoregulating sets near failure allows repetitions in reserve to serve as accurate indicators of intensity,⁵⁷ especially as trainees gain more strength training experience.⁵⁸ Additionally, our findings offer preliminary evidence that tracking intensity with repetitions in reserve in a remote coaching context may help prevent overreaching. Other long-term observational studies, such as Williams et al.², found that activity in the peripheral nervous system decreases with higher training volume load quartiles, which we did not observe. The prescribed training volume may not have been enough to cause parasympathetic withdrawal in recreationally trained individuals. One limitation of this study was that the increase in weekly training volume was not statistically significant, possibly due to reporting errors. We noted some missing weekly data from one participant, which may have impacted the analysis given our small sample size. This suggests that, without direct supervision, there's a risk of incomplete or inaccurate reporting of training. Our data suggest that chronic ST may not exert cumulative effects on HRV beyond 24 to 48 hours post-exercise, consistent with previous studies.^{4,14} Few studies have examined HRV over periods longer than six weeks; thus, the long-term impact of progressively intensifying ST on HRV remains unclear. Overall, high adherence and avoiding autonomic

overreach may have contributed to the observed increase in predicted 1RM squat. These mechanisms demonstrate how HRV-guided training frequency can boost commitment and deliver targeted performance benefits in remote coaching.

3.5 LIMITATIONS

Small sample size ($n = 9$) limited statistical power and precluded the use of a control group and the analysis of sex differences. Findings should be viewed as preliminary and intended to generate hypotheses, rather than being considered definitive conclusions. Despite the recruitment challenges, the research team encountered other issues; participants were initially required to complete a five items daily online survey on morning recovery perception. Because of the missing timestamps in the database, we could not analyze the correlation between HRV and perceived recovery.

It was important to note that neither facilitators nor barriers were evaluated for this project. Dietary intake was not controlled, which may have contributed to the observed increase in body fat mass and limited the interpretation of changes in muscle mass. The body composition was assessed using bioimpedance and ultrasound. Thus, small changes in body fat percentage should be interpreted cautiously, which may reflect measurement variability rather than physiological adaptations.

3.6 PRACTICAL APPLICATIONS AND FUTURE DIRECTIONS

This study provides preliminary evidence supporting the effectiveness of HRV-guided ST in remote settings. The data suggest that individualizing training frequency based on HRV does not impair recovery and may help maintain adherence in unsupervised environments. This approach is especially relevant in rural or remote areas where in-person coaching is limited³⁰. We recommend that coaches implement a remote-monitoring framework where daily HRV readings serve as a readiness "gatekeeper." In this system, green-light values indicate it's time for a training session, amber values suggest reducing the volume or intensity of the workout, and red values signal the need for active recovery. This approach is similar

to programmed sports watches that utilize heart rate, HRV or other metrics; and should be combined with a daily perceived recovery survey. Further research should investigate longer interventions, control dietary intake, and include larger samples to explore the chronic effects of HRV-guided ST on performance, recovery, and hypertrophy. Improved tools for capturing both HRV and subjective recovery would allow a robust exploration of recovery relationships.

3.7 STATEMENTS AND DECLARATIONS

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confidential information is not compromised. The detailed training program is available in the supplementary materials.

Declaration AI: The authors of this paper utilized AI software to enhance grammar, sentence structure, and paragraph organization, thereby improving readability. All the content was created and reviewed by the authors. AI was also used to format the test results into proper text.

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CHAPITRE 4

CONCLUSION DU MÉMOIRE

Le présent mémoire s'inscrit dans un contexte où persiste un besoin marqué de documenter objectivement la charge d'entraînement ainsi que les processus de récupération consécutifs à l'entraînement musculaire (De Oliveira et al., 2019). À ce jour, les kinésiologues disposent d'un nombre limité d'outils objectifs permettant d'évaluer de manière valide l'adaptation physiologique et l'optimisation des stimuli d'entraînement en musculation (Thamm et al., 2019). Cette lacune apparaît particulièrement saillante dans le contexte du suivi à distance. Malgré l'émergence de ces travaux, plusieurs limites persistent dans la littérature, notamment en raison du nombre restreint d'études longitudinales ayant examiné la récupération consécutive à l'entraînement musculaire à l'aide de la variabilité de la VFC. En effet, l'essor de la télésanté, notamment dans les régions caractérisées par un accès restreint aux services en présentiel, souligne la nécessité de développer des modalités de suivi valides et fiables susceptibles de se substituer à la supervision directe. Toutefois, cette modalité de prestation s'accompagne de contraintes spécifiques, dont une diminution documentée de l'adhésion aux protocoles d'entraînement en l'absence de supervision directe (Arikawa et al., 2011). Dans cette perspective, des travaux récents portant sur la VFC en contexte d'entraînement musculaire ont commencé à examiner son potentiel en tant qu'outil de suivi objectif, notamment en comparant l'adhésion à des programmes d'entraînement selon différentes modalités de supervision, soit avec supervision directe, sans supervision et avec autorégulation basée sur la VFC (Casanova-Lizón et al., 2025). Selon les données disponibles, l'autorégulation basée sur la VFC, en l'absence de supervision directe, est associée à une adhésion supérieure par rapport à une condition non supervisée, ce qui suggère son potentiel en tant qu'outil de soutien au suivi d'entraînement (Casanova-Lizón et al., 2025). Ces résultats sont cohérents avec ceux du présent mémoire, dans lequel une adhésion élevée au protocole a été observée, comparativement à celle rapportée dans d'autres interventions non supervisées menées auprès de la population générale (Davis et al., 2024 ; Casanova-Lizón et al., 2025).

Les principaux apports originaux de ce mémoire, au regard des travaux antérieurs, résident dans la dimension écologique du suivi à distance en milieu rural, l'utilisation d'une durée d'intervention fixe plutôt que d'un nombre prédéterminé de séances (De Oliveira et al., 2019), ainsi que dans l'intégration de mesures subjectives journalières recueillies à l'aide d'un questionnaire validé, inspiré de Flatt et al. (2018). La contribution au domaine réside dans la fourniture de données préliminaires qui soutiennent l'utilisation de la VFC comme outil favorisant l'adhésion en l'absence de supervision directe, tout en permettant de documenter l'adaptation du SNA à la charge d'entraînement. Cette approche a permis aux participants d'observer des gains de force sans compromettre l'état du SNP. Le projet de recherche s'inspire de divers travaux antérieurs, et l'aspect le plus novateur du protocole réside dans la collecte de données entièrement à distance, à l'exception des évaluations pré- et post-intervention effectuées en clinique. Le suivi repose sur des mesures quotidiennes de la VFC, utilisées comme outil décisionnel pour moduler la fréquence des entraînements, en remplacement de la supervision directe. Cette approche s'inscrit dans le cadre de l'essor de la télésanté, qui facilite l'accès aux services professionnels dans les milieux ruraux, où l'éloignement géographique limite souvent la possibilité de suivis réguliers en présentiel. Le protocole s'inspire des travaux de De Oliveira et al. (2019), qui proposaient une modulation de la fréquence d'entraînement basée sur des seuils de VFC. Cette approche a été retenue en raison de son potentiel d'adaptation à un contexte écologique à l'aide de technologies portables accessibles. Elle permettait également l'établissement de mesures de base valides de la VFC malgré l'absence de supervision directe pendant la période d'intervention de six semaines. Par ailleurs, le choix d'une durée d'intervention fixe découle des observations de De Oliveira et al. (2019), selon lesquelles un groupe s'entraînant à fréquence variable modulée par la VFC obtenait des gains comparables à ceux d'un groupe traditionnel en un temps réduit. Sur cette base, il était postulé qu'une augmentation de la fréquence d'entraînement, lorsque la récupération était jugée suffisante selon la VFC, pourrait potentiellement mener à des adaptations supérieures sur une période donnée. Malheureusement, en raison des difficultés de recrutement, l'absence d'un groupe contrôle n'a pas permis de valider cette hypothèse. L'intégration de mesures subjectives quotidiennes

s'appuie sur les travaux de Flatt et al. (2018), qui ont mis en évidence des corrélations importantes entre la VFC et des indicateurs subjectifs de récupération chez des nageurs de haut niveau. Cette composante a été retenue en raison de sa pertinence dans un contexte écologique et de son caractère encore peu exploré dans les études longitudinales en entraînement musculaire; toutefois, des difficultés à récupérer les données horodatées des participants ont empêché de réaliser l'analyse de corrélation entre la VFC et les données perceptives.

Les résultats fournissent des données préliminaires étayant l'efficacité d'un suivi à distance fondé sur la VFC. Ils suggèrent que l'utilisation de la VFC pour moduler la fréquence des entraînements pourrait contribuer au maintien du tonus parasympathique, tout en favorisant une forte adhésion au protocole et des améliorations significatives de la performance sur une période de six semaines. Ces observations s'inscrivent dans un contexte écologique représentatif des réalités des milieux ruraux.

La réalisation de ce mémoire de recherche a permis de consolider plusieurs compétences essentielles à la recherche appliquée, notamment en matière de conception et de mise en œuvre d'un protocole en contexte écologique. La gestion d'une collecte de données entièrement à distance a mis en évidence les défis liés au contrôle des variables, à la qualité des données et à l'adhésion des participants, renforçant ainsi l'importance d'anticiper ces contraintes lors de la planification d'études en milieu réel. Ce mémoire a également permis de développer une compréhension plus approfondie des enjeux associés au suivi à distance, notamment en lien avec l'intégration d'outils technologiques tels que la VFC et les mesures subjectives auto-rapportées. L'expérience acquise a mis en évidence la nécessité d'un équilibre entre la rigueur méthodologique et l'efficacité pratique afin d'assurer la validité et la pertinence des données recueillies. Enfin, cette démarche a contribué à renforcer une posture professionnelle orientée vers l'application des connaissances scientifiques, en favorisant une réflexion sur la transposition de méthodes de suivi objectivées dans des contextes réels de pratique en kinésiologie, notamment en milieu rural et en télésanté.

Ce mémoire comporte certaines limites à prendre en compte. La taille restreinte de l'échantillon, le recours à un échantillon de convenance non probabiliste ainsi que l'absence de groupe contrôle limitent la généralisation des observations et la capacité d'établir des inférences causales. De plus, certaines données auto-rapportées peuvent être sujettes à des biais de rappel ou d'estimation, et des contraintes techniques, telles que des problèmes d'horodatage, ont restreint certaines analyses. Par ailleurs, la portée de cette étude demeure exploratoire et s'inscrit dans un contexte spécifique de suivi à distance en milieu rural auprès d'une population de participants entraînés récréativement. Les résultats obtenus doivent donc être interprétés comme des données préliminaires, visant à soutenir l'efficacité et à orienter de futures recherches plutôt qu'à établir des conclusions généralisables à l'ensemble des populations ou des contextes d'entraînement.

Malgré ces limites, les résultats suggèrent que les professionnels pourraient adopter une approche de suivi à distance fondée sur la VFC afin d'orienter la prescription des séances (intensité élevée, intensité modérée ou récupération active). L'intégration d'un questionnaire journalier validé portant sur le sommeil, la fatigue et les courbatures pourrait offrir un portrait global et dynamique de l'état de récupération. Cette approche présente l'avantage d'être accessible, peu coûteuse et adaptée aux contraintes des suivis à distance.

Des recherches futures devraient inclure des échantillons de plus grande taille afin d'améliorer la puissance statistique et de permettre des analyses plus robustes, notamment en tenant compte de variables telles que le sexe et le niveau d'entraînement. L'intégration d'un groupe contrôle ou de conditions expérimentales supplémentaires permettrait également de mieux comparer l'efficacité d'un suivi basé sur la VFC par rapport à des approches d'entraînement traditionnelles. Bien entendu, le suivi de l'entraînement ne se limite pas à la modulation de la fréquence des séances. Une combinaison d'outils est donc souhaitable pour assurer des suivis de qualité. Il serait, par ailleurs, pertinent d'examiner les effets à long terme de ce type d'intervention sur d'autres marqueurs objectifs de récupération, notamment des marqueurs biochimiques. Les liens entre la VFC et les marqueurs auto-rapportés de récupération demeurent un sujet d'intérêt potentiel. L'inclusion d'un suivi de l'apport

nutritionnel contribuerait également à mieux contrôler les facteurs susceptibles d'influencer les adaptations de la composition corporelle.

Afin de personnaliser davantage la prescription, une analyse biomécanique pourrait être envisagée lors de la phase de pré-collecte. Dans une perspective de télésanté, l'intégration d'outils numériques permettant le suivi et l'analyse du mouvement (par exemple, l'évaluation vidéo à distance ou des applications de capture de mouvement) représenterait une avenue prometteuse pour enrichir le suivi des participants, notamment en documentant la qualité d'exécution des exercices et en soutenant l'individualisation des prescriptions. Enfin, le développement de plateformes intégrées combinant les mesures de VFC, les données d'entraînement, les indicateurs subjectifs et l'analyse du mouvement pourrait améliorer la qualité du suivi, renforcer l'adhésion au protocole et optimiser l'applicabilité clinique des approches de télésanté pour l'entraînement musculaire.

En somme, cette maîtrise suggère qu'un suivi de l'entraînement musculaire à distance, fondé sur la VFC, constitue une approche efficace et pertinente pour soutenir l'adhésion en l'absence de supervision directe, tout en permettant de suivre l'état de récupération et l'adaptation physiologique des participants. L'intégration combinée de mesures objectives et subjectives dans un contexte écologique et de télésanté apparaît prometteuse pour optimiser l'individualisation des prescriptions d'entraînement et améliorer l'applicabilité des interventions en milieu réel. Ces résultats préliminaires appuient ainsi le potentiel de la VFC en tant qu'outil pratique pour structurer et orienter le suivi de l'entraînement musculaire à distance.

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CHAPITRE 5

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