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Increasing lifting performances: Biomechanics for an optimized training

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Increasing lifting performances: Biomechanics for an optimized training

Abstract

More than sports, weightlifting and powerlifting are widely used in fitness/resistance training for sport performance. As they both consist of lifting additional weights they must be well executed to avoid injuries and enhance fitness and performance. To date, pieces of advice from experienced or graduated or self - proclaimed coaches, swarm in gyms and on the web, but very little are based on scientific knowledge. The same technical instructions are often given to men and women with different anthropometry and training history. As they are not individualized, these instructions could be at best suboptimal for most athletes, not enabling them to express their full potential and, at worst, dangerous and causing injuries.

The central objective of our project is the development and validation of an optimised personalized virtual human model.

On the one hand, a virtual mechanical model of an athlete squatting was numerically designed and set into motion by the development of a genetic algorithm minimizing a cost function.

On the other hand, an experiment was designed to measure the squat kinematics of experienced athletes.

The results of the simulation and experimentation were then confronted, the differences explained and areas of improvement listed.

Key-Words: optimization – squat – lifting – genetic algorithm - biomechanic - simulation

Résumé général

L'Homme travaille sa musculature depuis des milliers d'années. Des traces d'hommes pratiquant une activité physique destinée à développer la musculature et comprenant des charges additionnelles ont été trouvées dans plusieurs parties du globe et certaines remontent jusqu'à 3500 ans avant Jésus Christ. Quatre pays ont, plus particulièrement, eu des liens avec les sports de force dans l'antiquité : la Chine, la Grèce, l'Egypte et l'Inde. Ces pratiques, d'abord destinées à l'entraînement militaires ou liées à la religion sont, au fil des siècles, devenues des activités à part entière dont ont découlé des sports. Le plus connu d'entre eux est sans doute l'haltérophilie, sport de force mais surtout de puissance et de technique, l'haltérophilie fut l'un des premiers sports à intégrer les jeux olympiques modernes en 1896. Aujourd'hui, ce sport est constitué de deux levés : l'arraché et l'épaulé-jeté. Le premier consiste à prendre une barre au sol et à l'amener au-dessus de la tête, bras tendus, en un seul mouvement tandis que le deuxième levé est effectué en deux temps : la barre est d'abord amenée du sol aux clavicules durant l'épaulé puis des clavicules jusqu'à sa position finale au-dessus de la tête bras tendus lors du jeté. Contrairement à ce qu'un novice pourrait penser, l'haltérophilie n'est pas un sport mobilisant une forte masse musculaire sur le haut du corps mais bien un sport de puissance où le mouvement de la barre est engendré par la triple extension cheville genoux et hanche. Ainsi, on considère que la vitesse est une qualité aussi importante que la force en haltérophilie. C'est ce constat qui a poussé certains haltérophiles à développer un sport plus proche de la force pure dans les années 20 : la force athlétique. Contrairement à ce que son nom anglais,« powerlifting », laisse penser, la force athlétique est quasiment un sport de force pure. Ses trois mouvements le squat, le développé couché et le soulevé de terre sont en général effectués à des vitesses dix fois inférieures à celles d'un arraché.

Plus que des sports reconnus de haut niveau, la force athlétique et l'haltérophilie constituent la base de la préparation physique de tout sportif. En effet, les mouvements de ces 2 disciplines permettent le développement musculaire ainsi que l'amélioration de la coordination et de l'explosivité, qualités recherchées dans la plupart des sports collectifs ou individuels. Bien que pratiqués en masse, peu de chercheurs se sont intéressés à ces activités et encore moins à la manière dont l'exécution doit être adaptée en fonction de la morphologie du pratiquant. De ce fait, leur apprentissage reste à ce jour très empirique et certaines consignes telles que « les genoux ne doivent pas dépasser les pointes de pied lors d'un squat » s'avèrent suboptimale et même dangereuses pour certains pratiquants aux fémurs longs. L'objectif de recherche de cette thèse de doctorat est de participer à l'amélioration des performances des athlètes pratiquant l'haltérophilie et la force athlétique tout en minimisant leur risque de blessure par le développement d'un modèle humain virtuel personnalisé. Ce modèle ayant pour vocation de permettre l'analyse dynamique du corps en mouvement en le reliant aux mécanismes mis en jeu par l'athlète au cours de sa pratique.

Le manuscrit est articulé autour de 4 grands chapitres. Dans un premier temps l'état de l'art est étudié afin de mieux cerner l'avancée actuelle et les manquements de la recherche sur les sports de force ainsi que la simulation du geste sportif. Concernant les recherches sur les sports de force, il apparaît que la plupart des études se concentrent sur l'haltérophilie et n'ont pour vocation que l'observation du geste sportif. Il semblerait qu'une hypothèse majeure de ces études soit que l'haltérophile de haut niveau soit unique et est un mouvement parfait. En effet, aucune différentiation des individus n'est faite selon leur morphologie et, souvent, seules des moyennes des paramètres cinématiques sont proposées. Le constat est somme toute similaire concernant la force athlétique. De plus, les études tentant de mesurer l'influence des changements de certains paramètres sur la cinématique du mouvement sont bien souvent effectués sur des novices ou des athlètes de niveau régional auxquels un protocole et une exécution, souvent loin de leur schéma moteur habituel, sont imposés. Enfin les recherches concernant les blessures en haltérophilie et force athlétique remarquent que le taux de blessure est plus élevé chez les athlètes de niveau national que chez ceux de niveau international. De même, le taux de blessure diminue lorsque la pratique est supervisée par un coach par rapport à une pratique en autonomie. Ces deux constats renforcent l'importance de l'exécution du geste, non seulement pour la performance, mais aussi pour la réduction du risque de blessure.

Concernant l'utilisation de la biomécanique pour la performance sportive, plusieurs thématiques ressortent : l'application des lois de la mécanique pour la caractérisation du geste sportif, le besoin d'individualisation, les techniques de capture du mouvement, la modélisation du geste sportif et, pour finir, la simulation et l'optimisation du geste sportif. En effet bien que la plupart des études maîtrisent la capture et la modélisation du geste sportif, seules peu d'entre elles se sont intéressées à la simulation et l'optimisation de ce dernier. Pourtant, utiliser l'outil numérique pour expérimenter des changements techniques pourrait être une solution afin d'aider les sportifs de haut niveau à progresser sans leur imposer de protocoles expérimentaux contraignants. C'est d'ailleurs sur cet aspect que le projet de doctorat se veut innovant de par la création d'un modèle personnalisé qui servira de support aux simulations et sera validé par comparaison avec la modélisation des expérimentations. Ce travail sera effectué sur le squat, mouvement de flexion extension des membres inférieurs, celui-ci étant l'un des mouvements de compétition de la force athlétique mais aussi un facteur de performance en haltérophilie

Le second chapitre du manuscrit est donc dédié à la création du modèle mécanique ainsi qu'à la mise en place des simulations par le développement d'un algorithme génétique. Tout d'abord, suite à l'étude de l'état de l'art, un certain nombre d'hypothèses simplificatrices ont été choisies et un schéma cinématique a été établi. Comme le mouvement ne peut être dirigé par une ou plusieurs équations simples il a été décidé de discrétiser toutes les positions admissibles de ce dernier en se basant, d'une part, sur les mobilités articulaires et la répartition des masses données par la littérature et, d'autre part, sur l'intégration des lois de la mécanique. Une fois la base de données de toutes les positions admissibles créée, les lois de Newton sont appliquées afin de calculer, avec l'hypothèse du mouvement quasi-statique, les couples moteurs nécessaires à chaque articulation pour maintenir chaque position. Ainsi, la dernière étape est le choix d'un critère d'optimisation permettant de créer une trajectoire ou schéma moteur à partir de la base de données des positions. Après avoir testé sans succès plusieurs critères concernant la somme pondérée des couples à chaque articulation, il a été décidé d'utiliser une approche locale du travail des efforts internes utilisée dans la littérature prenant à la fois en compte les puissances articulaires frénatrices et motrices. Cette nouvelle fonction nécessite la mise en place d'un algorithme d'optimisation dont elle est le point central. Une nouvelle fois, afin de contrôler au maximum le processus, le choix a été fait de développer en interne un algorithme génétique dont la fonction coût serait celle évoquée précédemment. Une fois la convergence de cet algorithme vérifiée, il a été possible de lancer des simulations personnalisées qui seraient comparées aux résultats des expérimentations.

Afin de vérifier certaines hypothèses majeures et de comparer le résultat des simulations avec la réalité du terrain, une série d'expérimentations a été réalisée. Concernant le matériel scientifique, des caméras d'analyses du mouvement de la marque Optitrack^{TM} ainsi qu'une plateforme de force 6 axes de la marque Bertec^{TM} ont été utilisées. De plus, avant l'expérimentation, la fiabilité des caméras a été mesurée lors d'une phase de test. Pour réaliser un squat, 3 éléments sont nécessaires : une barre de 20 kg avec des manchons de 50 mm de diamètres, des poids calibrés allant de 1,25 kg à 25 kg et un support de barre pouvant être un rack de compétition ou une cage ou des supports individuels appelés chandelles. Seule la présence de ce matériel fut contrôlée et le choix fut fait de laisser les athlètes utiliser leur équipement personnel pouvant inclure : des chaussures des type haltérophilie avec talons surélevés ou des chaussures plates, des genouillères, une ceinture de type haltérophilie ou ceinture de force, des bandes de poignets. Seules deux demandes furent faites aux athlètes : porter une tenue moulante afin de pouvoir y fixer les marqueurs réfléchissants, faire au moins une série de squat à 70% ou plus de leur maximum théorique estimé (e1RM). Comme expliqué dans le premier chapitre, cette liberté fut volontairement laissée aux athlètes afin, d'une part, de disposer d'un plus grand nombre de sujets expérimentés sur le mouvement du squat et, d'autre part, de capturer le schéma moteur propre à chacun. Les différences d'équipement, de position de la barre ou d'écartement des pieds, généralement contrôlés dans les recherches scientifiques, pourront ensuite servir de critères de regroupement s'ils influencent de manière significative la cinématique du mouvement.

Une fois les expérimentations menées à bien une comparaison des résultats est effectuée. Avant la confrontation finale, il est nécessaire de traiter les données des expérimentations et des simulations afin de les mettre sur des formats comparables. Pour cela les données expérimentales suivantes sont collectées : longueurs des segments basées sur la distance entre deux marqueurs successifs, position de la barre sur le dos, masse de l'athlète, masse de la barre. Ces dernières sont implémentées à la simulation afin que l'algorithme génétique calcule la trajectoire qu'il considère comme optimale, c'est-à-dire minimisant la fonction coût. Cette trajectoire simulée est alors comparée à la trajectoire expérimentale de l'athlète en utilisant les critères suivants : vitesse angulaire du fémur au cours du temps, répartition des couples articulaires, position du centre de pression au cours du temps et kinogram du mouvement. Il apparaît tout d'abord que l'algorithme génétique permet de calculer une trajectoire réaliste, résultat important et encourageant. Ensuite on remarque que les couples articulaires maximums ne sont pas répartis de la même manière. En effet, la simulation demande un couple maximal plus élevé au niveau de la cheville plutôt que de la hanche, ce qui est l'inverse en réalité. Cette différence peut s'expliquer par le fait que, le modèle étant mécanique uniquement, il ne tient pas compte des masses musculaires disponibles à chaque articulation. Cette différence pourrait sans doute être corrigée en modifiant la fonction coût dans l'algorithme implémentée génétique et en implémentant le ratio couple / couple disponible en se basant sur des données de la littérature ou des mesures effectuées individuellement. La principale différence entre simulation et expérimentation réside dans la position du centre de pression au cours du mouvement. Selon l'algorithme génétique, le centre de pression du système {athlète + barre} devrait être positionné au-dessus des talons au début de la poussée et se déplacer progressivement jusqu'à se situer sous l'articulation métatarso-phalangienne à la fin de l'extension. D'après les expérimentations, le centre de pression effectue, indépendamment de l'athlète, de la charge ou de l'équipement utilisé, le trajet inverse. C'est cette constatation qui a monopolisé le temps de travail lors de la dernière année. Plusieurs hypothèses ont été formulées pour expliquer cette différence, notamment un manque de mobilité des Européens et un manque de stabilité de l'appui talon. Les recherches dans la littérature, tout comme les expérimentations, n'ont pu permettre de valider aucune de ces hypothèses. Finalement, bien qu'elle n'ait pu être étudiée en raison du manque de temps, la dernière hypothèse évoquée qui semble la plus prometteuse est que l'appui doit être sur l'avant du pied pour permettre la contraction des extenseurs de cheville. Cette hypothèse est d'ailleurs en accord la pratique des cyclistes qui placent leurs fixations de pédales sous l'articulation métatarso-phalangienne bien qu'ils pourraient en théorie les placer sous les talons.

Le travail effectué pour ce projet se veut innovant et prometteur. La méthodologie mise en place a permis de reproduire le mouvement humain pluri-articulaire de façon réaliste. Cette même méthodologie peut, à ce jour, être généralisée à d'autres activités sportives telles que le tir à l'arc ou le golf. Néanmoins, la simulation se trouve limitée quant à l'optimisation et il serait sans doute nécessaire de passer sur un modèle musculosquelettique pour prendre en compte les subtilités du mouvement humain.

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Chapter 1 Introduction

The first signs of weightlifting among people date back to 3500 BC. Evidence of people developing their strength before gyms existed has been found all over the world. In India, training was associated with military and religion, while in Ancient Greece, mythology contains various stories of gods lifting rocks. Furthermore, the statues of Greek gods confirm that a high value was placed on a well-trained body. Evidence of people training in ancient times has also been found in China, Ancient Egypt, and Scotland.

Nowadays lifting activities can mainly be separated into three competitive sports: Weightlifting, powerlifting and strongman.

Weightlifting has been part of the Olympic Games since 1896, and after several changes in the lifts, it was decided in 1972 that it would consist of two events: the snatch (lifting a barbell overhead in one movement) and the clean and jerk (lifting a barbell overhead in two movements)(Stone et al., 2006). As lifters are required to bring the bar overhead, weightlifting is a sport that demands both acceleration and technical abilities. Therefore, some lifters argued that it did not solely demonstrate the pure strength of athletes. Consequently, powerlifting was created and gained popularity in the 1950s when the fitness industry started to thrive. The International Powerlifting Federation (IPF) has governed this sport since 1972. This 50-year-old sport requires maximal strength on three lifts: the squat, the bench-press, and the deadlift. (Ferland and Comtois, 2019). For a long time, only equipped competitions existed in which lifters wrapped their knees with bands and wore special suits for each lift to enhance their performance. However, since 2013, a classic division has also been established. Before the classic division existed, the strongest nations in powerlifting were Eastern European countries such as Russia and Ukraine. However, since 2012, the United States of America and Western European countries have been growing stronger every year. In 2022, after the Open and Junior World Championships, France ranked as the top country worldwide in the junior division and second in the Open division.

In addition to being recognized as Olympic and World Games sports, powerlifting and weightlifting movements are used by athletes in many sports to increase their physical capabilities and enhance their performance. (McGuigan et al., 2012). Nowadays, regardless of the sport, most elite athletes, whether in individual or team sports, have a strength and conditioning coach in addition to their sport coach. These coaches help athletes grow their muscle mass and gain strength. As a result, even though the injury rate of gym training is less than four injuries per 1000 hours of training, athletes take great care to train safely and prevent injury. (Parkkari, 2004), it is important for lifters and athletes using powerlifting and weightlifting movement to use a correct technique to limit those risks and improve fitness and performance.

In the literature, it seems widely accepted that different anthropometrical characteristics induce different movement strategies (Cholewa et al., 2019), yet most studies on performance don’t take segments lengths into account. This oversight, once transferred to the gyms, induce that the same technical instructions are often given to lifters with different anthropometry and training history. As they are not individualized, these instructions could be at best suboptimal for most athletes, not allowing them to express their full potential and, at worst, dangerous and causing injuries. The most striking example being to keep the knees from moving past the toes (Fry et al., 2003).

This PhD is part of a large project that aims to develop an optimized, personalized virtual human model based on experimental measurements on athletes, with an evaluation of the risk of injury at the limits of performance. Models that calculate optimal technique based on limb length and joint torque production capabilities could be implemented in training to help athletes visualize the difference between how they currently move and how they should move. This approach could accelerate the learning phase, improve performance, and reduce the risk of injury(De Stefani et al., 2020). The objective of this PhD was to develop the first skeletal model and test its major hypothesis on elite athletes.

Chapter 2 Context of the study and state of the art

2.1 Lifting

Lifting activities are mostly being studied for their impact outside of the gym. Actually, resistance training has many advantages:

- Maintain muscle mass for elderly people (Saengrut et al., 2021)
- Increase bone density (Benedetti et al., 2018; Layne and Nelson, 1999)
- Increase sprint performance (Comfort et al., 2012; Styles et al., 2016)
- Improve general health (American College of Sports Medicine, 1998; Westcott, 2012)

Sit-to-stand, is very similar to a bodyweight squat. As it is the most demanding activity for elderly people and the main criteria for independency, its optimization has been deeply studied (Bajelan and Azghani, 2014; Bobbert et al., 2016; Caruthers et al., 2020).

During their professional activity, many workers have manual material handling tasks, that can be compared to deadlift. These are the main risk factors for musculoskeletal disorders such as low-back pain, the most common painful condition human experienced (Violante et al., 2015). Once again, multiple studies exist on this topic as finding solutions to reduce the risk of injury is critical (Denis et al., 2020; Harari et al., 2020; Porta et al., 2021).

From a competitive point of view, sports that involve lifting weights include weightlifting, powerlifting, and strongman, with cross-training using movements from all three. However, as the International Olympic Committee (IOC) only recognizes weightlifting and powerlifting, this section will only focus on these two activities.

2.1.1 Weightlifting

Weightlifting was one of the sports introduced in the first modern Olympic Games in 1896. Currently, this sport consists of two competition lifts carried out consecutively. The first lift is the snatch: it consists in taking the bar on the ground and lifting the weight off the ground to overhead in one movement. To perform the second movement, the athlete has to take the bar on the ground and lifts the weight off the ground to overhead in two movements: the clean and the jerk.

This mis-known sport has grown quite a lot since the advent of Crossfit (Verass, 2016): a multi-sport practice, booming worldwide, combining mainly powerlifting, weightlifting, gymnastics and endurance sports. Therefore, training for Crossfit events requires learning and practicing the snatch and the clean and jerk. Several members of the USA weightlifting national team used to compete in Crossfit.

Firstly, it should be noted that weightlifting is a sport that is very well-suited to biomechanical analysis. This is because the sport is practiced in a small, defined area and the movements can be easily captured. The first studies on the subject were written in the 1940s and were later compiled into a manual published by the International Weightlifting Federation (IWF).(Vorobyev, 1978).

A literature review was carried out on the snatch in 2014 (Ho et al., 2014). The snatch is widely considered to be the most technical lift in weightlifting, which is why it is more extensively studied compared to the clean and jerk. Additionally, the pull phase of the clean is very similar to that of the snatch, which means that the technical tips given for the snatch are often applicable to the clean as well. However, the jerk, which is the final phase of the clean and jerk, seems to be the least studied movement to date. Therefore, this state-of-the-art will focus on the two pulling lifts: the snatch and the clean.

Studies on the snatch (Bai, 2008; Campos et al., 2006; Gourgoulis et al., 2002; Medvedev, 1988; Takano, B., 1993) highlight the fact that this movement can be split up in 6 positions (1 / Start position, 2 / Bar et knee Level, 3 / Power Position, 4 / Full extended, 5 / Catch, 6 / Fully Recovered) separated by 5 phases (A/ First Pull, B / Transition, C / Second Pull, D / Turnover, E / Recovery) as illustrated on Figure 1. For the clean, the phases are identical until the catch that does not happen overhead but on the clavicles and will be followed by a front squat and not an overhead squat.

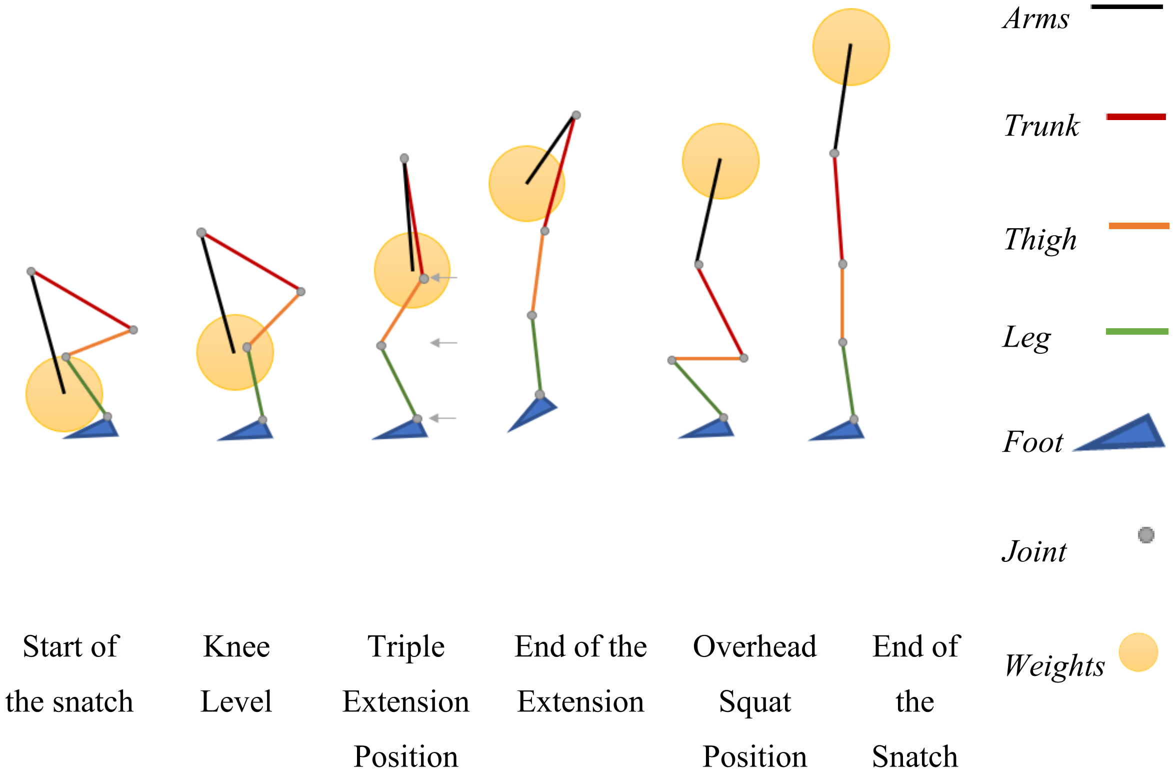


Figure 1: The phases of the snatch

It is admitted that, despite respecting the same rules and breaking down into phases, every lifter adopts his own technique based on his experience and morphology (Gourgoulis et al., 2002; Isaka, Tadao; Okada, Junichi; Funato, Kazuo., 1996; Stone et al., 1998; Wang, X., 2009). When an athlete has acquired the necessary skills and technique over time, their goal is to repeat the same movement as precisely and consistently as possible during each training session. This process is the same for all athletes, regardless of their age or experience level, as they strive to improve their performance through deliberate practice and repetition (De Stefani et al., 2020) To the best of my knowledge, there is no existing study that specifically identifies the learning process of the optimal technique for a given individual, nor the precise contribution of this technique to performance in weightlifting. While there have been studies that investigate the biomechanics of the snatch and clean and jerk, as well as the effects of different training programs and techniques on performance, a comprehensive analysis of the learning process and its impact on performance is still lacking. However, ongoing research in this area may provide more insight into these topics in the future.

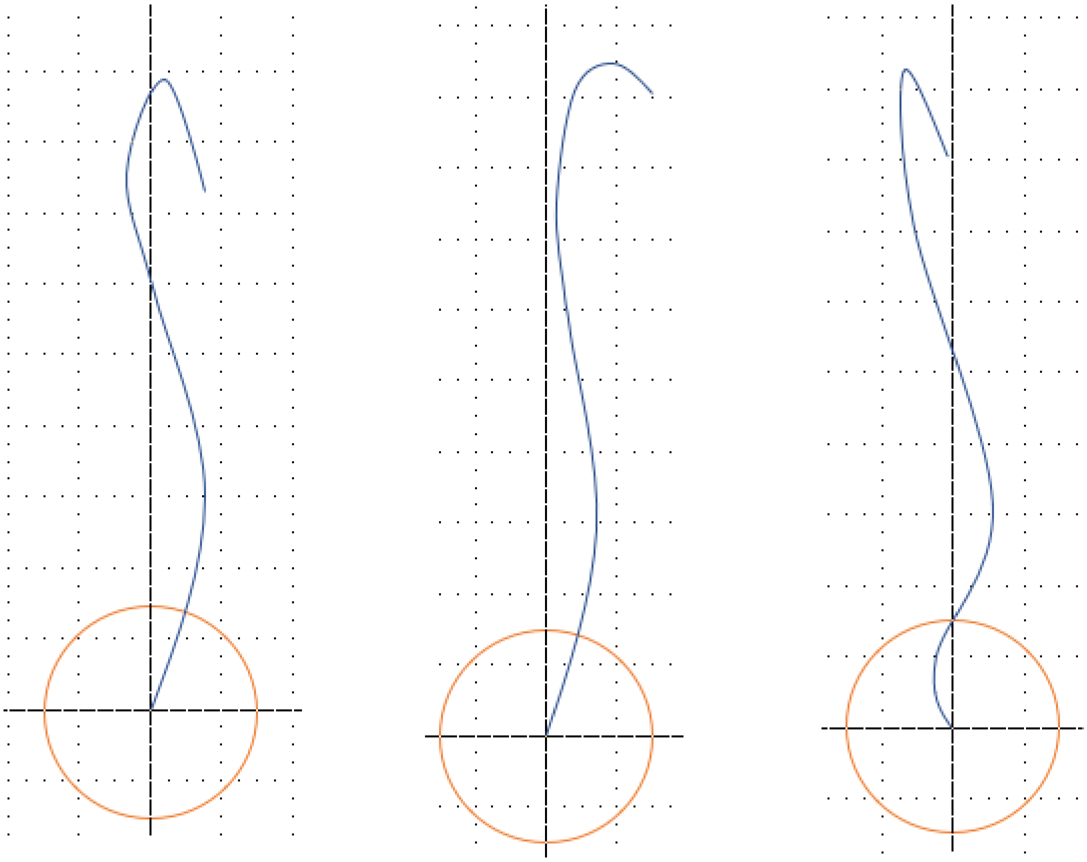
During the snatch and the clean, two systems are in motion: the athlete and the bar.

2.1.1.1 The bar

It is quite easy to know precisely its movements thanks to a reflecting marker at the end of the bar and a camera; three data are then classically used.

The first one is the maximum height reached by the bar. The higher the bar goes, the more time the athlete will have to “get under” and catch it. This value, at the end of full extension, is about 70 % the size of the athlete (Bai, 2008; Campos et al., 2006; Stone et al., 1998). Some studies provide a range of height of 1.15m to 1.27m (Campos et al., 2006; Gourgoulis et al., 2004, 2002) which appears irrelevant, given that it is normal that a woman weighing less than 49kg (smallest Olympic women category) measuring 1.50m does not raise the bar as high as a man weighing more than 109 kg (largest Olympic men's category) measuring 1.90m. The distance between the highest point reached by the bar and the level at which it is caught has also been identified as an efficiency factor of the technique (Gourgoulis et al., 2000; Isaka, Tadao; Okada, Junichi; Funato, Kazuo., 1996; Nagao et al., 2019; Wang, X., 2009) If this distance is small, it means the athlete was able to "fall" and catch the bar quickly. However, the literature does not specify how to gain in efficiency during the catch but only observes the differences between high-performance athletes and amateurs (Gourgoulis et al., 2004).

The second data usually analysed is the trajectory of the bar. Three typical S trajectories have been distinguished and are shown in Figure 2.



Trajectory A

Trajectory B

Trajectory C

Figure 2 : Different types of bar trajectory in the snatch

Each athlete will use one technique or the other, depending on their learning experience and physical characteristics. A key factor for success in the lift, regardless of the chosen technique, is the horizontal displacement of the bar between lift-off and catch (Yi-Hsuan Chen and Hung-Ta Chiu, 2011). A study has also found a correlation between the horizontal distance between the bar and athlete during the second pull and the success of the lift (Yi-Hsuan Chen and Hung-Ta Chiu, 2011). Additionally, a study by Gourgoulis (Gourgoulis et al., 2009) suggests that the total displacement vector of the pull (horizontal and vertical) is significantly different between successful and unsuccessful attempts. These results align with the principles of mechanics. As the goal of the lift is to raise the bar as high as possible, efforts made to move it in the sagittal plane are useless and can unnecessarily tire the athlete. Furthermore, the further the bar is from the athlete, the greater the lever arm, complicating the pull. However, these calculations, which may be obvious to a mechanical engineer, have never been published and only observations are reported.

The speed profile of the bar is the last data measured. During each pulling phase, the bar's speed increases, and it is crucial that this speed does not decrease during the transition phase when the bar is at knee level (Figure 1). During the successful lifts listed in articles (Gourgoulis et al., 2004, 2002; Hoover et al., 2006; Liu et al., 2018; Okada et al., 2008; Stone et al., 1998) the bar's speed reaches its maximum at the end of the second pull, when the athlete is fully extended. Applying the fundamental principle of dynamics to the bar shows that for it to rise as high as possible, its maximum speed must be achieved when the athlete's feet leave the ground. For high-performance athletes, maximum bar speed is an essential factor for performance (Isaka, Tadao; Okada, Junichi; Funato, Kazuo., 1996). However, some studies on leisure lifters do not share this opinion (Ho et al., 2011). This result discrepancy probably arises from the fact that, at an amateur level, the learning process combined with the fear of getting under the bar is often problematic.

2.1.1.2 The lifter

The parameters analysed on the lifter are Joint angles, Double bending of the knees, Bar/cervical/hip angle.

A study on amateurs finds that the position of the joints when the bar takes off is directly linked to the success or not of the lift (Ho et al., 2011). At the same time, other studies have observed movement of the ankles, knees, and hips and plotted curves of these joint angles evolutions during the lift (Bai, X., Wang, H., Zhang, X., Ji, W., Wang, C., n.d.; Gourgoulis et al., 2009, 2004, 2002; Kim et al., 2019; Mastalerz et al., 2019; Wang, X., 2009; Wang, X and Pylypko, V, 2009). Unfortunately, none of them has experienced modification of these parameters to increase performance. The results of the observation were also not compared with dynamic calculations on the {athlete + bar} system to compare the discrepancy between theory and practice and see if the strongest athletes are, as supposed in literature, stronger thanks to their technical qualities or, on the contrary, only thanks to their muscular capacities.

To get more upright and set themselves in a better position to create power during the second pull, the athletes bend their knees during the transition phase when the bar is over the knees.

This movement is called the double-bending knees and is a phenomenon regularly identified and interpreted as evidence that the stretch-shortening cycle of the leg extensors is used to increase the force on the second pull (Gourgoulis et al., 2000; Isaka, Tadao; Okada, Junichi; Funato, Kazuo., 1996; Krol, H., 2001; Stone et al., 2006). Another possible interpretation is that this new position balances the lever arms to allow each muscle group to produce simultaneously maximum contraction to vertically accelerate the bar. Indeed, an extension of the hips alone, although the glutes, the hips extensors, are the most powerful muscles of the human body, could cause a greater displacement of the bar in the sagittal plane and less in the frontal plane.

Finally, the bar/cervical/hip angle has been analysed by two studies (Chen, YH and Chiu, HT., 2011; Chiu, HT and Liang, JL., 2010) both of which find that the lower this angle is during the transition phase and the second pull, the more chances there are of the lift being successful. This confirms the finding that the closer the bar is to the body, thus reducing the lever arm, the more effective the movement is.

2.1.1.3 Future directions

Firstly, while several studies have observed the kinematic variables during the lift, only one has attempted to establish a link between these parameters and the success of the lift (Ho et al., 2011). Moreover, this study only had one novice participant and focused solely on joint angles at take-off. The literature review (Ho et al., 2014) highlights the need for new studies to identify the key variables influencing lift success. This is the goal of the Ph.D. project, which aims to apply the laws of mechanics to identify these parameters before experimentation. This approach could enable the investigation of how modifying these parameters influences performance.

Secondly, the idea that a lifter's technique varies based on their morphology and physical abilities is widely acknowledged but not yet well-researched. However, individualizing the lifting technique is considered crucial to optimizing performance. Therefore, it is essential to delve further into this topic. By creating a personalized model for each athlete, as proposed in the Ph.D. project, it would be possible to numerically study the most promising techniques and compare them with observations to guide the athlete towards the most efficient and tailored movement. This approach could enable the athlete to realize their full potential and reduce the risk of injury.

Finally, while real-time feedback is more beneficial than feedback given over an extended period, none of the studies conducted to date have provided this feedback. However, by identifying critical parameters upstream and utilizing non-invasive and easy-to-setup biomechanical equipment, as proposed in the project, it may be possible to offer real-time feedback on the most promising technique. This approach could allow athletes to progress more quickly without adding volume to their training, thereby reducing the risk of injury and allowing for more recovery time.

2.1.2 Powerlifting

Powerlifting consists in 3 movements: Squat, Bench-press and Deadlift. It was created in the 30's by weightlifters finding that weightlifting wasn't expressing enough the absolute maximal strength. The first official competitions took place in the 70's with the creation of the International Powerlifting Federation (IPF) in 1973 (Augustin and Stebbins, 2014). For a long time, only equipped lifting existed. Equipment (suits and knee wraps) were first created to protect lifters but, soon, became real performance enhancers (Godawa, 2011) and the best lifters were not necessarily the strongest but the ones who would have the best suit and knew how to gain the most of it (up to 25% performance increase in squat, 30% in bench press and around 10% in deadlift). As a result, studies published on powerlifting before the creation of the raw/ classic world championship, in 2012, cannot be considered relevant. The only ones that could be kept are those about Para powerlifting – classic bench press at the Paralympic games – which was first included as a Paralympic sport in 1984.

Although squatting and deadlifting both involve a double extension of the knee and hips, they differ significantly in their execution due to the positioning of the barbell. The barbell is held on the elbows during squats, and the extension is simultaneous. In contrast, during deadlifts, the barbell is on the floor, and the extension is not simultaneous. While there are relatively few studies on powerlifting as it is not an Olympic sport, it comprises the three main lifts that physical therapists use to enhance the physical qualities of athletes from all disciplines. Therefore, there is a considerable amount of research on squats and bench pressing, especially on this issue. Additionally, squats are often compared to the sit-to-stand movement, which is the most demanding activity for elderly individuals and is well-documented. Furthermore, deadlifts are sometimes compared to handling, a demanding work task for many people that requires research to reduce the injury rate associated with it.

In 2019 was published a systematic review about classic powerlifting (Ferland and Comtois, 2019) that was supplemented for this state of art with a PubMed research with the following strategy : (powerlift [All Fields] OR powerlifter [All Fields] OR powerlifter's [All Fields] OR powerlifters [All Fields] OR powerlifters' [All Fields] OR powerlifting [All Fields]) AND ("2018/08/01"[PDAT]: "3000/12/31"[PDAT]).

The subjects of the studies were anthropometrics (Ferland et al., 2020a, 2020b; Ferland and Comtois, 2019; Reya et al., 2021), polygenic profile (Moreland et al., 2020), stretching (Spence et al., 2020), programming (Ferland and Comtois, 2019; Godawa, 2011; Travis et al., 2021, 2020), rate perceived exertion (RPE) (Ferland and Comtois, 2019), squat (Ferland and Comtois, 2019; Murawa et al., 2020; Sjöberg et al., 2020), bench press (Ferland and Comtois, 2019; Reya et al., 2021; Ribeiro Neto et al., 2020), and injuries (Dudagoitia et al., 2021; Ferland and Comtois, 2019; Sjöberg et al., 2020). As this PhD is about movement optimization, only anthropometrics, kinematic, and technology are going to be developed in this state of art.

2.1.2.1 Anthropometrics

Regarding anthropometrics, (Keogh et al., 2007) found that male powerlifters tend to be very muscular individuals, exhibiting very high mesomorphism. This theory is also supported by (Ferland et al., 2020a) showing a high correlation coefficient between hip circumference/ height and waist circumference/height meaning that powerlifters tend to be compact and have a high muscular volume compared to their height. Relationship between bodyweight and absolute muscular strength exist and this relation is even stronger between lean body weight and muscular strength. As a result, the study by (Marković and Sekulić, 2006) expressed the importance of adjusting performance in powerlifting and weightlifting to height in addition to muscle mass. This in-lights again the importance of anthropometric in performance.

(Keogh et al., 2007) studied only the powerlifting lifted total which is the sum of the heaviest squat and bench-press and deadlift succeeded. They found they powerlifters have large girths and bony breadths and relatively average segment length/ratios. The fact that they did not find segment ratio tendency could be explained as they have only studied the powerlifting total and not the load lifted for each movement. Actually, what seems to be the optimal ratio tends to differ between lifts. For example, people with shorter arm have less range of motion in bench press but more in deadlift. As a result, if ones want to see the impact of anthropometrics on performance, the squat, bench-press and deadlift should be studied independently. This theory is supported by (Reya et al., 2021) that have shown that the brachial index was strongly associated with 1RM bench press. The influence of anthropometric on deadlift variant performance was studied in the article of (Cholewa et al., 2019). To do so, they took deadlift naïve subjects and, after measuring their segment lengths, made them test their 1RM with two different positions, conventional and sumo, in random order. Then, they tried to correlate segment length and ratio with deadlift preference.

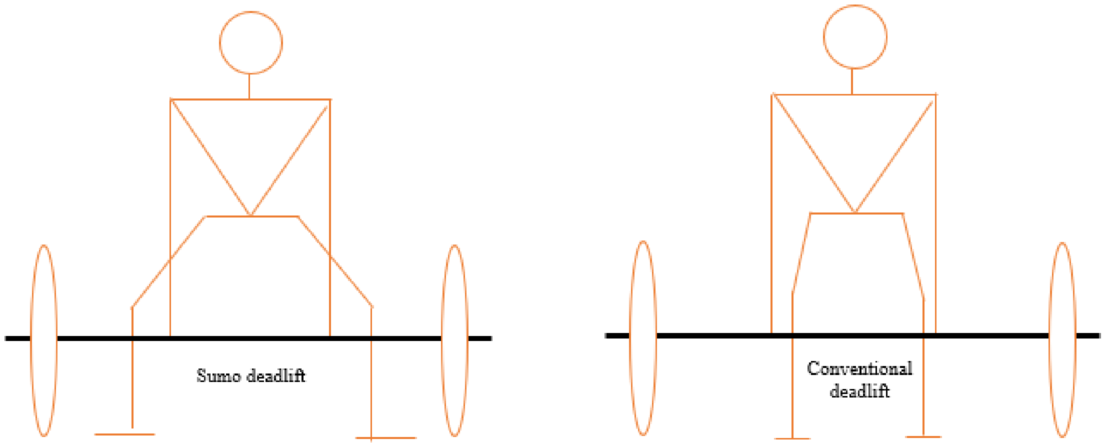


Figure 3 : Deadlift techniques

Actually, none of these studies did case series and tried to explain how and why anthropometrics was influencing performance. In addition to this, mastering a lift take years and, in studies using naïve or recreational athletes, the results tend to be different that the ones on elite athletes, as shown by (Glassbrook et al., 2019). As a result, the reason they have pulled heavier on one variation rather than one the other could be because of their muscular weakest link or just that they got used to lifting a weight from the floor and performed better on the second 1RM test. These reasons could explain why they (Cholewa et al., 2019) have never reached significance on how anthropometrics affect deadlift stance preference, even though the tendency seemed the right one to powerlifters. Even though it's not perfect, a better way to assess determinants lifting performance, would be to measure segment length of experienced lifters who've tried to master their lifting techniques and see how these ratio correlate with their performance in squat, bench-press and the 2 types of deadlift.

Furthermore, neither was studied how people with different anthropometrics and especially segment length ratio could have different muscle and bar trajectory strategies to lift the most weight, what would be the beginning of an individualization process.

2.1.2.2 Kinematics

Kinematic of squat was the most studied of the 3 lifts, the reasons for this could be that squatting movement has many variations such as squat jump or counter movement jump that are used for athletes of different sports or sit-to-stand which is the most demanding action for elderly people. The downside of it is that only few of these studies are made on the "powerlifting" squat (back squat with low bar position) and only (Glassbrook et al., 2019; Hecker et al., 2019; McLaughlin et al., 1978; Swinton et al., 2012; van den Tillaar et al., 2020) made their studies on the movement of experienced lifters with samples going from 10 to 18 athletes. As a result, for most variables, they could not reach significance. The lack of elite lifters in studies could be explained by the rigidity of the experimental protocols. Powerlifting is a very organized sport and athletes usually have training plans they are strictly following up to 20 weeks before competitions. As a result, most of them would not volunteer to participate in studies that would disturb their training and slower their progression.

Yet, (Glassbrook et al., 2019) compared elite and recreational lifters doing high bar and low bar back squat and found significant differences between both type of lifters and "indicates that resistance trained individuals should not be compared/combined with well-trained athletes when comparing such a technical movement as the High Bar Back Squat (HBBS) or Low Bar

Back Squat (LBBS) as there is an apparent influence of expertise on the performance of these techniques".

A first solution to that would be, as it has widely been done in weightlifting, (Akkuş, 2012; Harbili, 2012; Ikeda et al., 2012) to use video footage of national and international competition to measure kinematics, the difference between both sports being that there are no spotters in weightlifting but there can be up to 5 around a lifter in powerlifting, what makes the acquisition more difficult. Another solution is that, instead of forcing athletes into a special protocol, it could be interesting to acquire their planned training and then cluster the acquisitions based on the technique / %1RM / sex and so on. This type of acquisition could attract more lifters and enable searchers to create a huge exploratory database on which they would be able to study more than one aspect.

That being said, out of the 5 studies, 4 are about the influence of changing parameters (barbell placement or type) on the kinematics of the squat. (Glassbrook et al., 2019) found the same kinetics between LBBS and HBBS despite greater absolute loads being lifting in LBBS. Even though they suggest that LBBS is a more efficient technique they could not explain why. One could suggest that they should have clustered their group of participants to see if anthropometrics were to influence technique preference and performance. (Hecker et al., 2019) studied the difference between a standard barbell and a safety squat barbell (SSB), they found a decrease of performance around 11% with the SSB as well as an increase in activation in the lower trapezius (+50.3%). No significant results about the kinetics and kinematics were found once again. (Swinton et al., 2012) compared the traditional squat with the powerlifting squat and box squat. According to them, a traditional squat is performed with a narrow stance and knees travelling past the toes, while a powerlifting squat is with a wider stance and vertical shin. In their protocol, they made the subjects use the 3 conditions (traditional vs powerlifting vs box) at 3 different loads of 30/50/70% of their competition squat 1RM in random order with only 2min rests between each condition. Adapting to a technique takes repetitions and by changing between techniques and loads with no warm up, there is little chance that the technique is going to be optimal for each condition. In their study, (van den Tillaar et al., 2020) used low bar and high bar squatting only, they made their subject find the heaviest load the can do 5 repetition with, also called the 5 repetition maximum (5RM) in one condition and then switch to the other. To have comparable values they equated the stance width as well as the shoe condition and the load used for comparison (weightlifting shoes) for both tests. The conclusions were that there is no difference in barbell and joint kinematics between both conditions but an increased muscle activity in the rectus femoris, vastus medialis, and lower part of the erector spinae with the high-bar condition. One reason could be that because the absolute load is the same, the lifters are easier in the low bar squat condition and do not adapt their technique as they would be closer to failure. The other reason for not reaching significance, as expressed earlier, could be because of the small sample size once again.

Finally, even though it is the oldest study, (McLaughlin et al., 1978) studied the kinematic of the back squat of some the US Senior National lifters and found the most detailed results:

- Trunk extensors produce the biggest torque during the parallel squat, more then shank and thigh ones.
- The difference between static, quasi-static and dynamic calculus differ from less than 10%.

2.1.2.3 Technology

As the objective of the PhD is the movement itself and not the genetic nor the programming part of powerlifting, the articles about polygenetic, programming and RPE (a subjective way to assess difficulty of the training) won't be developed here. The main fact is that individualisation is already studied in the programming field, mainly with RPE or Velocity Based Training (Suchomel et al., 2021), so why does it not exist in the technical area ?

Competitive squat was only studied to measure the differences between high bar and low bar back squat (Ferland and Comtois, 2019; Murawa et al., 2020). The results are that low bar back squat tends to enhance performance as well as the activation of the posterior muscle chain. The gluteus maximum is the main extensor of the hip joint and also the strongest muscle of the human body. As a result, it seems logic that, by lifting low bar, the level arm at the hip is going to increase and so does the gluteus maximum recruitment. These ideas could be the start of an optimisation process based on muscular strengths and weaknesses of an athlete.

2.2 Biomechanic for sport performance

2.2.1 Mechanics in sports

The application of mechanical principles is one of the most used way to analyse movement efficiency and strategy; their accuracy and limitations have been studied by (Smith, 2004). The conclusions are that even a point mass model can be enough to demonstrate some major principles such as the efficiency of a rowing technique compared to the other. Also, rigid body model can be used to apply inverse dynamic, calculate the joint torques and measure the power; this calculus were also proven to be effective in the rowing action by (Smith, 2004).

Mechanical factors have also been used to understand injuries such as low back pain (Nourbakhsh and Arab, 2002) as well as to model overuse injuries occurring in sport (Edwards, 2018). In the later article, injuries are treated as mechanical constraints and loading cycles, cumulative load and magnitude are used to study the mechanical fatigue in biological tissue, which provides foundation for future research on the topic.

However misconceptions exist regarding the application of mechanical principles in biomechanics as (Vigotsky et al., 2019) expressed in their article. According to him, Newton’s third law, scalar and vector quantities as well as weight and gravity are often incorrectly applied to models, thus leading to errors.

2.2.2 Need for individualization

Individualisation has already been studied in many fields and mostly on adapting the teaching modality to the student. Liu et Zhu conducted a study on sports biomechanics students with different teaching modes based on the profiling of each student (Liu and Zhu, 2020). The results of the studies were very conclusive and support the effectiveness of individualization.

Individualisation in the sport field is mostly being studied regarding the training modalities. Baptista (Baptista, 2020) measured that, depending on the position on field, players would not have the same amount of high-intensity runs, accelerations, decelerations and sprints during the game. Its conclusion is that each player should train according to the demands of its position. The same logic was applied by Boichuk et al. regarding the basketball coordination preparation (Boichuk et al., 2018). Their factor analysis revealed four factors of the preparedness of players: rapid reconstruction of motor actions, kinaesthetic differentiation, complex reaction and spatial orientation. To them, the training program of each player should be balanced between these factors depending on the capabilities of the athlete. Even though they did not find significant results, studies were also conducted on the force velocity profiling as well as the personalised motor imagery (Lindberg et al., 2021; Lindsay et al., 2020).

Another way of individualizing training could be to adapt the technic to the anthropometry of the athlete. As the Figure 4 shows, people with different anthropometrics cannot move the same way.

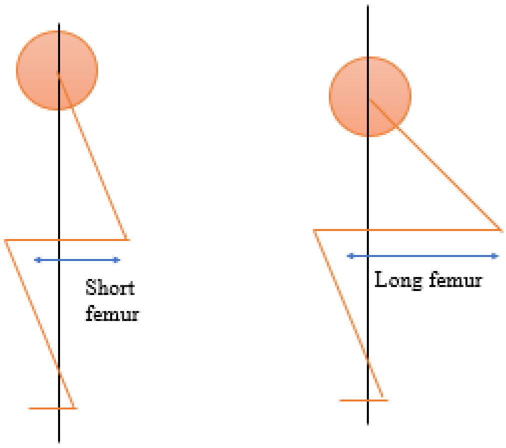


Figure 4 : Change of the trunk inclination because of the femur length

Anthropometrics have been studied in the literature as a performance factor for running and swimming (Black et al., 2020; Mooses and Hackney, 2017; Morais et al., 2021). It appears that swimmers with higher arm span and hand length are better in sprint performance and that East African runners, who are part of the best runners in the world, tend to have a higher legs/trunk ratio. The general knowledge is that elite athletes do have an optimal technique (Enoka, 1979). But if elite athletes of one sport have the same anthropometrics, does it make sense to teach the same movement to athletes with different anthropometrics? Even if they do not have the optimal limb length ratio to become the best in their sport, couldn't it be interesting to help those athletes optimize their capacity whatever their anthropometrics?

The only study that exists on the technique change regarding anthropometrics was about the barbell trajectory in the snatch lift (Musser et al., 2014). Searchers used footage of an international competition to measure horizontal displacement of the barbell during the lift knowing from measurements of the lengths of the lifters' segments. They found that, in a same bodyweight category, elite women weightlifters would have a different horizontal displacement depending on their thigh and trunk lengths. This finding supports the theory that technical instructions should be personalised for each athlete.

2.2.3 Capturing movement

Different systems exist to capture movement in the sport field and can be divided into four measurement system categories: Electromagnetic Systems (EMS), Image processing systems (IMS), Optoelectronic systems (OMS) and Inertial Measurement Unit (IMU).

EMS might be the most known and used one. Also referred to as GPS, it can be used in outdoor and indoor team sport such as soccer, rugby or basketball to track the motion of players during the games. This technology is made of a small box placed in a sport bra that can be used both in training and on game day.

Even though this GPS can measure with 90% accuracy (Rampinini et al., 2014) the total distance (TD), high-speed ratio (HSR > 4.17m.s−1), very high-speed ratio (VHSR > 5.56m·s−1), mean power (Pmean), high metabolic power (HMP > 20 W · kg−1) and very high metabolic power (VHMP > 25 W·kg−1), it cannot inform scientists on the movement strategy used by players to create motion, which is the goal of this PhD. As a result, this technology is not suited for this study.

IMU is a technology that can recognize the orientation of a device by combining an accelerometer, a gyroscope as well as a magnetometer. As for EMS, IMU is minimally invasive and can be used in large spatial volumes. In addition, devices can be put on each limb of a subject to calculate precisely the acceleration of each one. The main problem with this technology is that it cannot be used to calculate position and, if the signal is integrated, large integration drift would appear.

OMS are the most accurate measurement systems of all and are often referred to as the gold standard in the literature (Corazza et al., 2010; Rampinini et al., 2014). OMS uses active or passive markers fixed on anatomical sites of the athlete and special cameras that detect the light of the markers and there position by triangulation. The validity of OMS was studied by (Furtado et al., 2019; Nagymáté et al., 2018; Nagymáté and Kiss, 2018; Nagymáté and M. Kiss, 1970). According to (Furtado et al., 2019) who studied the Optitrack^{TM} devices (the same cameras available at the lab), the measurement error depends on the camera model chosen and, for a velocity of 0.2m/s -the average squat velocity- the average error should be between 0.005m for the weakest camera and 0.0025m for the best one. As the amplitude of the squat movement is around 50cm for the knees, hips and shoulders, the average error should represent less than 1% of the total movement. The main drawbacks of this technology are: it can only be used in restricted area (Begon et al., 2009) with at least two cameras in line of site of each marker (Panjkota, 2009; Spörri et al., 2016) and without interfering lights (Spörri et al., 2016). The difference between active and passive markers is that active ones give more accurate data but need cables and batterie, which can prevent some athletes from having enough freedom to move. Finally, this system needs to be calibrated every time the set-up is altered. To sum up, this technology is a lab one and can't be transferred on field measurement. In lifting sports, for example, even if the area of movement is fixed and restricted, lights, spotters and vibrations of the bars falling on the floor could alter the calibration and prevent from having good acquisitions.

The last technology is IMS. The most known IMS is the Kinect^{TM} sensor used for gaming (Bt Ismail and Basah, 2015). The principle of this technology is to use cameras to capture movement and digitally analyse it afterward. The main advantage of this technology is that it is vision based while the other systems were sensor based (Zhong and Chang, 2004). As a result, it can be implemented to capture data in competition of individual sport, even in larger volumes. The main drawbacks are that most of the time the movement recognition is not real-time as the videos need to be processed to recognize motion. Furthermore, its accuracy is around 0.05m and degree errors can be up to 10° (Fernandez-Baena et al., 2012) while the OMS one is 0.01m, which is not the best for precision acquisition.

As our study is about an individual indoor sport practiced in a small area, the technologies used will be IMS and OMS.

Another way to capture data is to use force plate to measure the centre of pressure of the system as well as the direction and intensity of the force applied on the ground. Even though it is possible to calculate this data by derivation of the position of the joints knowing the mass and inertia of the segment, having a force plate enables to visualize in real time the forces and suppress the errors that could appear with the inertia approximation of the segment and possible lack of accuracy of acceleration signals. In the past years, portable force plates have been developed that can be implemented in the training areas.

If one wants to implement a musculoskeletal model, or measure the activation of muscles throughout the movement, it is also possible to use surface electromyography (EMG). This technology consists in wireless electrodes fixed on the skin. The electric potential between both electrodes is then calculated to measure the Central nervous system (CNS) command to the muscles (Merletti and Muceli, 2019). EMG are widely used in sport biomechanics (Taborri et al., 2020) but are not mandatory in kinetics modelling.

2.2.4 Modelling movement

Musculoskeletal and especially subject specific modelling has grown in popularity with the advances of computing power. Its use may enhance the understanding of scientist regarding the kinetic, kinematic and muscle recruitment of different movements arising from manual material handling (Skals et al., 2021) to sit-to-stand (Bobbert et al., 2016) or sport performance (Nakashima and Chida, 2021).

In the literature, most biomechanical models are developed on dedicated simulation softwares such as OpenSim^{TM} (Delp et al., 2007) or The AnyBody Modelling System^{TM} (AMS) (Damsgaard et al., 2006). The advantage of using such softwares is mainly the gain in time. The human is a complex system and, to simulate accurately the gait, the simplest legs models have more than 35 degrees of freedom and 80 muscle tendon units (Rajagopal et al., 2016). Hence, most of the studies on motion simulation were made using premade models on dedicated softwares (Bajelan and Azghani, 2014; Caruthers et al., 2020; Myers et al., 2015; Rajagopal et al., 2016; Roelker et al., 2017; Schellenberg et al., 2015; Skals et al., 2021; Valente et al., 2014). As the human body is composed of around 600 muscles with individual internal moment arms, it is nearly impossible to create a perfect musculoskeletal model and, when implementing the same markers movement on different models, they provide different answers based on which and how muscles have implemented. Those differences were measured by Roelker et al (Roelker et al., 2017) between four models to simulate the gait, they found differences up to 462 N peak rectus femoris force, which means that depending on the objective of the studies, maybe using a generic model is not the best option to have precise values.

Also, OpenSim^{TM} and AMS^{TM} enable measuring kinetics on recorded motions but until recently with the Moco extension (Dembia et al., 2020), they did not allow for optimization of the movement. Hence, if one wanted to do both, they might have to develop their own numerical model.

As a result, to control the possibilities of the model and to optimize its motion, it might be more interesting to develop a simpler mathematical version displaying the features needed for the sport movement rather than to use a generic model.

2.2.5 Simulation and optimization

Rahmati and Mallakzadeh (Rahmati and Mallakzadeh, 2014) explained in their article the two methods to find an optimal technique. According to them too, “the optimum technique varies among athletes, since the anthropometric body dimensions vary”. This is the reason why they chose not to record the motion of champion weightlifters, but they rather chose to use a mathematical model and find an optimal trajectory. To do so, they used Minimax approach with multi-objectives functions based on normalized total torque, power and barbell vertical velocity. The barbell vertical velocity being added because in weightlifting, as the bar needs to finish above the head, one criterion is to give the bar the highest vertical velocity.

Once the objective functions are chosen, constraints need to be applied to create a realistic model. In weightlifting kinematic, kinesiology, physiology, balance maintenance and non-interference constraints had to be prescribed. In squat, as the bar is maintained still on shoulders, the same constraints, except non-interference, should be imposed.

All those data are then implemented into a genetic algorithm for the optimization process. They used the genetic algorithm between t and t + dt on each time. Using this strategy instead of an optimization on the full trajectory has the advantage to save computation time and could also lead to create a trajectory that minimizes only a little the objective function at the beginning but could lead the model into such a position that is far from optimal in the middle of the trajectory. Hence, a better genetic algorithm should work on the full trajectory instead of a step by step basis.

Glazier explores in his article how can biomechanical feedback be used to enhance sports performance (Glazier, 2021). The main problems regarding biomechanical feedback are the accuracy of the data collected depending on the sensors used as well as the choice of data to collect and how they will provide knowledge on the captured movement. The three aspects of sport gesture are coordination, control and performance. Using the kinematic data as well as the outcome of the motion, it is easy to give feedback on performance and coordination. The problem is completely different for control which can be defined as "an outcome of coordination"(Glazier, 2021). Hence, coordination is how the body organises itself to move that way and is not measurable by sensors. To the author, as mathematical models only capture a small part of the human organization, they cannot calculate the intrinsic coordination of the athlete nor provide an individual optimum technique. Hence, to help elite athletes achieve their optimal performance, the best way to use biomechanics would be to capture kinetic as well as kinematic data regularly to have data about how the athlete moved when he felt and performed the best and try to channel him toward this goal all year long.

2.3 Conclusion on the state of art and PhD objectives

The existing literature on lifting mainly focuses on the squat movement but only describes it as well as the influence of outside parameters modification on the outcome. Our goal is to innovate and, as Rahmati and Mallakzadeh (Rahmati and Mallakzadeh, 2014) did, to try to simulate and optimize the numerical model of the athlete, to compare with experiments and understand the underlying coordination needed to be performed.

On the contrary of the actual literature and as (Glazier, 2021) suggested, movement will be captured in training conditions without forcing the athletes onto a special protocol. That way, more athletes will likely take part in the project and help create a larger exploratory database. Once this is done, kinematic and kinetic data will be clustered to find what athletes with the same movement pattern have in common and what differs between athletes with different patterns.

The main goal of this project is to understand the anthropometrics factors that affect squat technique to tend toward an individualized optimum model.

Chapter 3 Modelization

3.1 Creation of the mechanical model

3.1.1 General Hypotheses

The human is a complex system and, to model it, it is necessary to make simplifying assumptions. To study movement, it is important to use, at least, a skeletal model. In addition, some studies also implemented muscles to create a musculoskeletal model. As expressed in the state of art, Roelker enlighten that model complexity could enhance the differences between experimental measures and simulation (Roelker et al., 2017). To control the complexity of our model, the decision was made to develop our own skeletal model so it can be mastered and implemented on a generic platform such as Matlab™. The general hypotheses of this model (Figure 5) were:

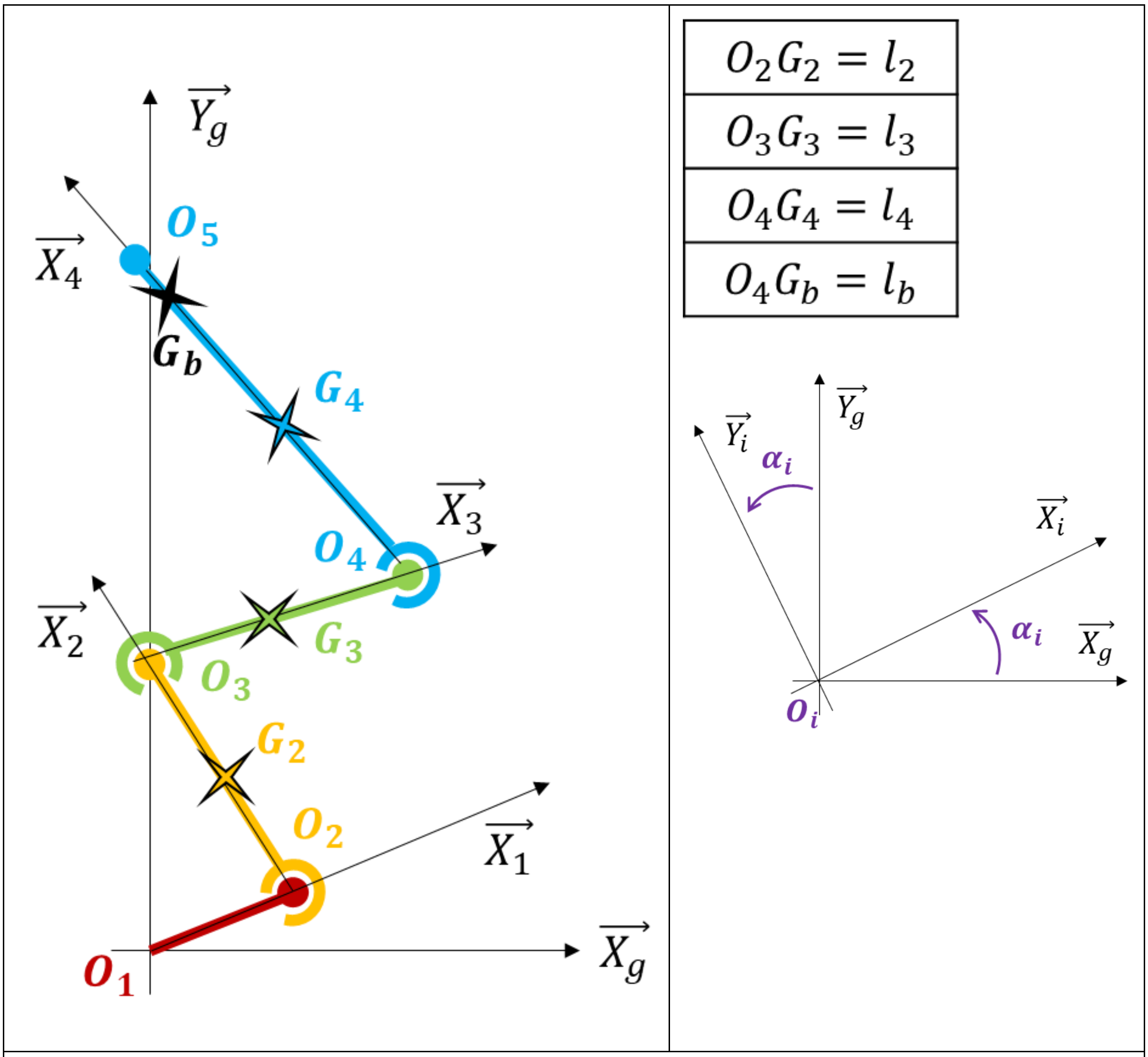
HYP 1 -The human limbs can be modelled with rigid bodies: foot (1), shank (2) , thigh (3), trunk (4)

HYP 2 -The squat movement is considered symmetrical and can be studied in the sagittal plane only, as a 2D movement

HYP 3 -The ankle, knee and hip joints are considered perfect pivot links with no friction consideration.

HYP 4 – Only the concentric (= ascending) part of the squat is considered

The kinematic diagram of the model is presented in Figure 5.



$O_2G_2 = l_2$

$O_3G_3 = l_3$

$O_4G_4 = l_4$

$O_4G_b = l_b$

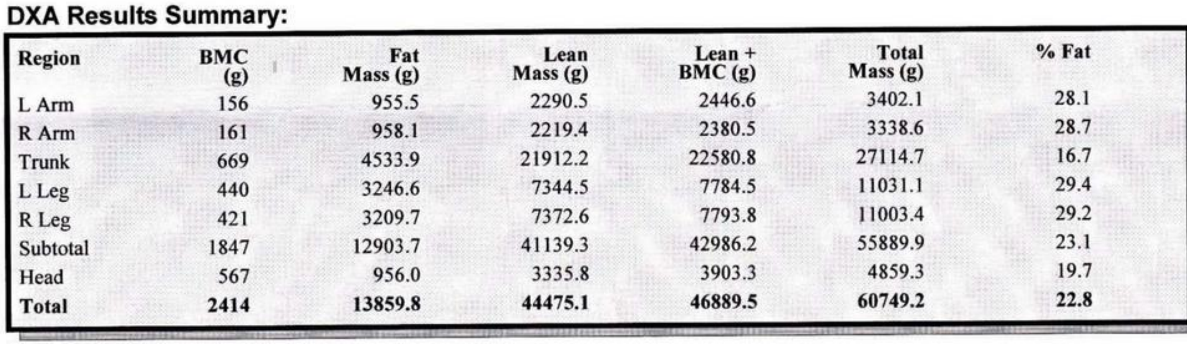
Figure 5: Kinematic diagram of the mechanical model

3.1.2 Development of the discrete model

According to (McLaughlin et al., 1978) the squat motion can be reasonably modelled as a quasi-static motion. Hence this was chosen as a first approximation. To begin, the variables needed for the model were defined.

- The human body was separated into four rigid bodies: foot, leg, upper leg and trunk. These segments were the same as those used in other articles (Flanagan et al., 2015; Glassbrook et al., 2019; McLaughlin et al., 1978; van den Tillaar et al., 2020) except for the foot which was added. The foot length was taken as the distance between the toes and the malleolus. The trunk was considered as one straight rigid body from the hip to the shoulders.

- The position of the bar was defined as the distance between the 7th cervical vertebra and the bar. The bar was considered fixed on the vertebral column without any horizontal offset.
- The mass of the bar was entered and divided by 2 as only the left side of the body is modelled
- The distribution of the bodyweight mass was taken from the previous DXA results of a French powerlifter, see Table 1, and divided by 2
- The centre of mass position of each segment was taken from research data of (Dempster and Gaughran, 1967) and the segments were considered as point masses placed at the centre of mass of each limb.
- The glute mass was not specifically considered
- The head was not modelled



DXA Results Summary:

Region	BMC (g)	Fat Mass (g)	Lean Mass (g)	Lean + BMC (g)	Total Mass (g)	% Fat
L Arm	156	955.5	2290.5	2446.6	3402.1	28.1
R Arm	161	958.1	2219.4	2380.5	3338.6	28.7
Trunk	669	4533.9	21912.2	22580.8	27114.7	16.7
L Leg	440	3246.6	7344.5	7784.5	11031.1	29.4
R Leg	421	3209.7	7372.6	7793.8	11003.4	29.2
Subtotal	1847	12903.7	41139.3	42986.2	55889.9	23.1
Head	567	956.0	3335.8	3903.3	4859.3	19.7
Total	**2414**	**13859.8**	**44475.1**	**46889.5**	**60749.2**	**22.8**

Table 1 : Bodyweight distribution of a woman powerlifter (with permission)

Then, the ranges of motion were defined:

- To respect the IPF rule (International Powerlifting Federation, 2022) the upper leg needs to be around 5° under parallel (see Figure 6), this approximation was confirmed by calculus on athletes of different bodyweights. The upper leg range of motion was set from -5° to 90° (stand erect).

Female -52kg

Measure: 9°

Female -69kg

Measure: 5°

Male -83kg

Measure: 6°

Male -105kg

Measure: 5°

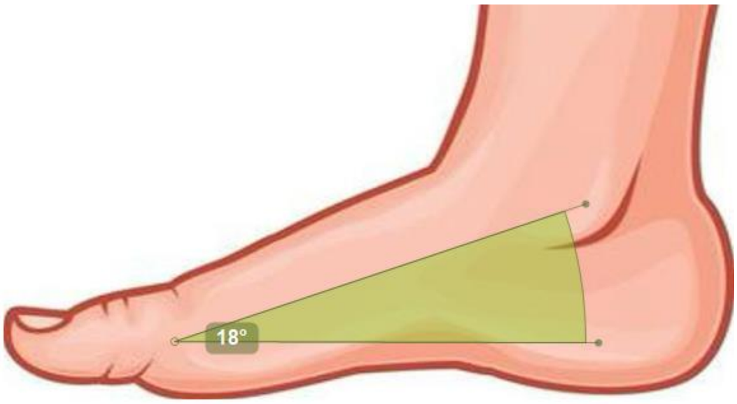
Figure 6: Angle between the femur and the surface of the thigh at the beginning of the concentric phase

- The ankle flexion mobility is set at 50° from literature data (Burns and Crosbie, 2005). The range of motion of the ankle was set from 90° (stand erect) to 140° relative to the ground
- As the foot is considered as a rigid link going from toes to the malleolus, it is not horizontal. The angle between the horizontal from the metatarsophalangeal joint and the foot was calculated on video footages and set at 18°(Figure 8). If the athlete wears weightlifting shoes with elevated heels, it is possible to modify and increase the angle. The toes of the lifter were considered at the origin and the angle of the foot was set constant during all the lift.
- The common knowledge is that the centre of mass of the total system {lifter +bar} needs to be above the mid of the foot during all the lift.

The hypotheses listed above are presented in Figure 7. All the variables and ranges of motion were then stored into matrices.

Angle of the top feet relative to the floor	$\alpha_1 = 18^\circ = cte$
Position of the front foot	$x_{O_1} = y_{O_1} = 0$
Range of Motion of the Ankle relative to the floor	$90^\circ \leq \alpha_2 \leq 140^\circ$
Range of motion of the thighs relative to the floor	$-5^\circ \leq \alpha_3 \leq 90^\circ$

Figure 7 : Range of motion of the joints and position

	Figure 8 : Measure of an angle between the malleolus, metatarsophalangeal joint and horizontal

It was chosen to discretize all the acceptable positions and store them, and to do so loops were coded as explained under. Kinematic Diagram & Change of Basis are available in figure 5

The angles $\alpha_i, i \in [2,3]$ are discretized in equidistant values in their range of motion α_{3_j}, $j \in [1 \dots m]$ & α_{2_k}, $k \in [1 \dots n]$

For each upper leg position α_{3_j}

For each ankle mobility value α_{2_k} :

- Set the model into a vertical trunk position as illustrated on Figure 9 ($\alpha_{4_k} = 90°$, $\forall\, k \in [1 \dots n]$)
    - Calculate the positions of the joints with a vertical trunk
        - $x_{O_{i_k}} = x_{O_{i-1_k}} + O_iO_{i-1} * \cos(\alpha_{i_k})$
        - $y_{O_{i_k}} = y_{O_{i-1_k}} + O_iO_{i-1} * \sin(\alpha_{i_k})$
        - The joint between the upper leg and trunk is located at the hip
        - The joint between the leg and upper leg is located at the centre of the knee
        - The joint between the foot and the leg is the malleolus
        - The foot is considered fixed on the ground
    - Calculate the position of the bar
        - $x_{O_{b_k}} = x_{O_{4_k}} + l_b * \cos(\alpha_{4_k})$
        - $y_{O_{b_k}} = y_{O_{4_k}} + l_b * \sin(\alpha_{4_k})$
        - The bar is considered fixed on the back during all the lift
- Calculate the hip angle needed to have CoM_tot the total centre of mass (CoM) above mid-foot
    - Calculate the CoM position of each body using the ratio ($ratio_i$) from the litterature (Plagenhoef, 1983)
        - $x_{G_{i_k}} = x_{O_{i_k}} + ratio_i * (x_{O_{i+1_k}} - x_{O_{i_k}})$
        - $y_{G_{i_k}} = y_{O_{i_k}} + ratio_i * (y_{O_{i+1_k}} - y_{O_{i_k}})$
    - Calculate CoM1 the leg+upper-leg CoM position using the barycentre formula

        - $x_{G_2+G_{3_k}} = \frac{m_2 * x_{G_{2_k}} + m_3 * x_{G_{3_k}}}{m_2+m_3}$
        - $y_{G_2+G_{3_k}} = \frac{m_2 * y_{G_{2_k}} + m_3 * y_{G_{3_k}}}{m_2+m_3}$

    - Calculate the position of $G_4 + G_{b_{current}}$ the current trunk+bar CoM
        - $x_{G_4+G_{b_{current_k}}} = \frac{m_4 * x_{G_{4_k}} + m_b * x_{G_{b_k}}}{m_4+m_b}$
        - $y_{G_4+G_{b_{current_k}}} = \frac{m_4 * y_{G_{4_k}} + m_b * y_{G_{b_k}}}{m_4+m_b}$
    - Calculate $x_{G_4+G_{b_{goal}}}$, the necessary horizontal position of $G_4 + G_b$ to have x_{CoM} above mid foot
        - $x_{G_4+G_{b_{goal_k}}} = \frac{(m_2+m_3+m_4+m_b) * x_{CoM} - (m_3+m_2) * x_{G_2+G_{3_k}}}{m_4+m_b}$
    - Calculate B_1 the horizontal distance between $G_4 + G_{b_{current}}$ and $G_4 + G_{b_{goal}}$
        - $B_{1_k} = abs(x_{G_4+G_{b_{goal_k}}} - x_{G_4+G_{b_{current_k}}})$
    - If this distance is more than the hip to bar distance A_1: set the configuration as impossible, see Figure 10
        - $A_{1_k} = abs(y_{G_4+G_{b_{current_k}}} - y_{O_{4_k}})$
        - The trunk is considered one rigid body and the efforts between every vertebral body when the trunk is angled are not considered
    - Calculate the necessary angle of the trunk relative to the floor to reach CoM2_goal
        - $\alpha_{4_k} = asin\left(\frac{B_{1_k}}{A_{1_k}}\right) + \frac{\pi}{2}$
        - We want to control the CoM of the whole system instead of just the bar
- Set the model into the position with the angle of the hip
    - Calculate the new position of the shoulders
        - $x_{O_{4_k}} = x_{O_{3_k}} + O_4O_3 * \cos(\alpha_{4_k})$
        - $y_{O_{4_k}} = y_{O_{3_k}} + O_4O_3 * \sin(\alpha_{4_k})$

    - Calculate the new bar position
      - $x_{O_{b_k}} = x_{O_{4_k}} + l_b * \cos(\alpha_{4_k})$
      - $y_{O_{b_k}} = y_{O_{4_k}} + l_b * \sin(\alpha_{4_k})$
    - Calculate the CoM position of the trunk
      - $x_{G_{4_k}} = x_{O_{4_k}} + ratio_4 * (x_{O_{5_k}} - x_{O_{4_k}})$
      - $y_{G_{4_k}} = y_{O_{4_k}} + ratio_4 * (y_{O_{5_k}} - y_{O_{4_k}})$
    - Calculate the CoM of the system
      - $x_{CoM_k} = \frac{m_2 * x_{G_{2_k}} + m_3 * x_{G_{3_k}} + m_4 * x_{G_{4_k}} + m_b * x_{G_{b_k}}}{m_2 + m_3 + m_4 + m_b}$
      - $y_{CoM_k} = \frac{m_2 * y_{G_{2_k}} + m_3 * y_{G_{3_k}} + m_4 * y_{G_{4_k}} + m_b * y_{G_{b_k}}}{m_2 + m_3 + m_4 + m_b}$

  - Calculate the joint static torques
    - To do so, apply the principles of static (**Erreur ! Source du renvoi introuvable.**)

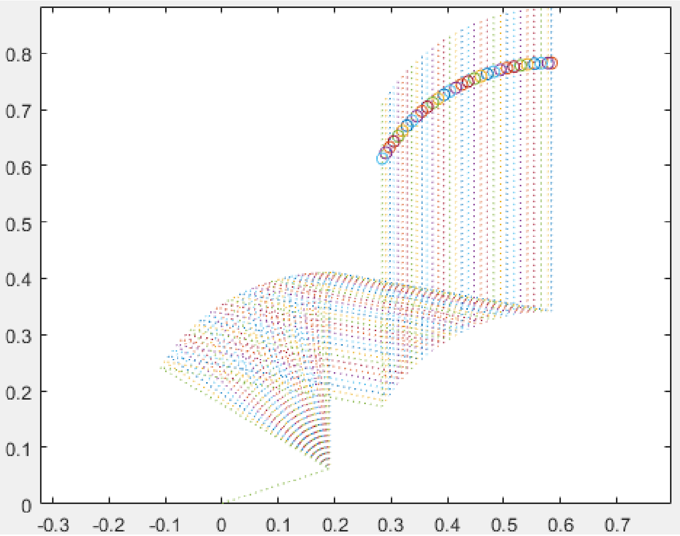


Figure 9: First positioning of the model with a vertical trunk

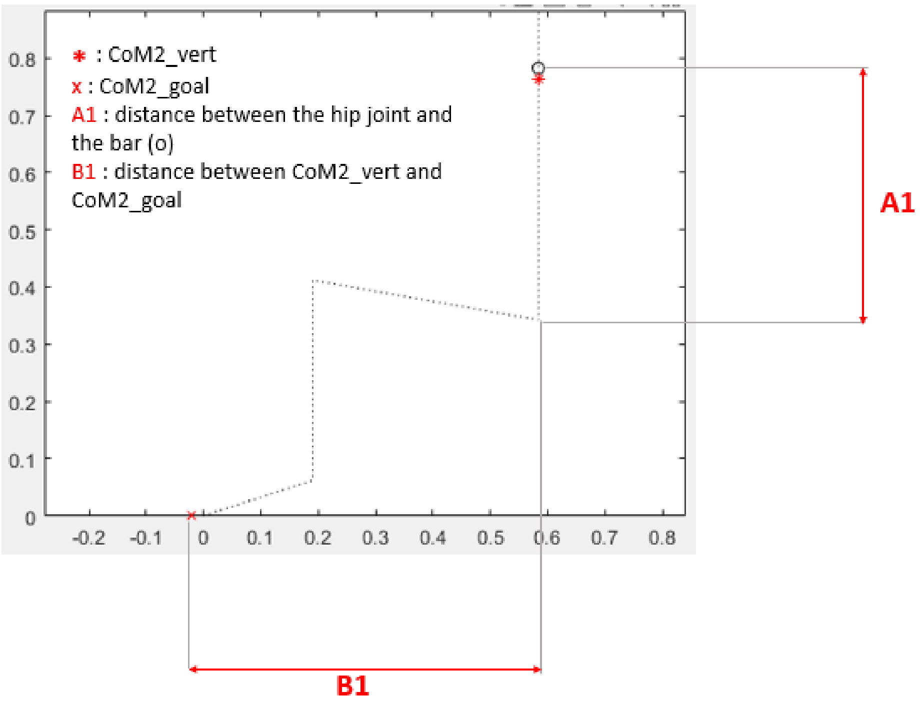
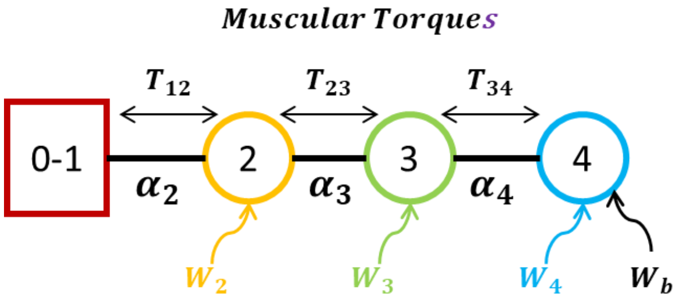


Figure 10 : Impossible configuration (A1< B1)

1- Bond graph



2- Equation

To calculate the muscular torque T34 the formula $\overrightarrow{\Sigma M(0_4)_{/S4}}.\vec{z} = 0$ is applied. To do so, the solid S4 is isolated and the external mechanical actions are listed:

- Weight of 4 in G4 $\overrightarrow{M_{W_4}(O_4)}.\vec{z} = l_4 * w_4 * g * \cos(\alpha_4)$
- Weight of the bar in Gb $\overrightarrow{M_{W_b}(O_4)}.\vec{z} = l_b * w_b * g * \cos(\alpha_4)$
- Pivot joint in 04 around z axis $\overrightarrow{M_{pivot_{34}}(O_4)}.\vec{z} = 0$
- Muscular torque T34 in 04 around z axis $\overrightarrow{M_{musc_{34}}(O_4)}.\vec{z} = T_{34}$

The result is: $\overrightarrow{\Sigma M(0_4)_{S4}}.\vec{z} = 0 \quad => \quad l_4 * w_4 * g * \cos(\alpha_4) + l_b * w_b * g * \cos(\alpha_4) + 0 + T_{34} = 0$

Hence $T_{34} = -(l_b * w_b + l_4 * w_4) * g * \cos(\alpha_4)$

3- Result

The same principle is applied to S3+S4 and S2+S3+S4 and, once projected on the ground base, the muscular torques are:

$$T_{34} = w_b * g * (x_{G_b} - x_{O_4}) + w_4 * g * (x_{G_4} - x_{O_4})$$

$$T_{23} = w_b * g * (x_{G_b} - x_{O_3}) + w_4 * g * (x_{G_4} - x_{O_3}) + w_3 * g * (x_{G_3} - x_{O_3})$$

$$T_{12} = w_b * g * (x_{G_b} - x_{O_2}) + w_4 * g * (x_{G_4} - x_{O_2}) + w_3 * g * (x_{G_3} - x_{O_2}) + w_2 * g * (x_{G_2} - x_{O_2})$$

Table 2: Application of the principles of static

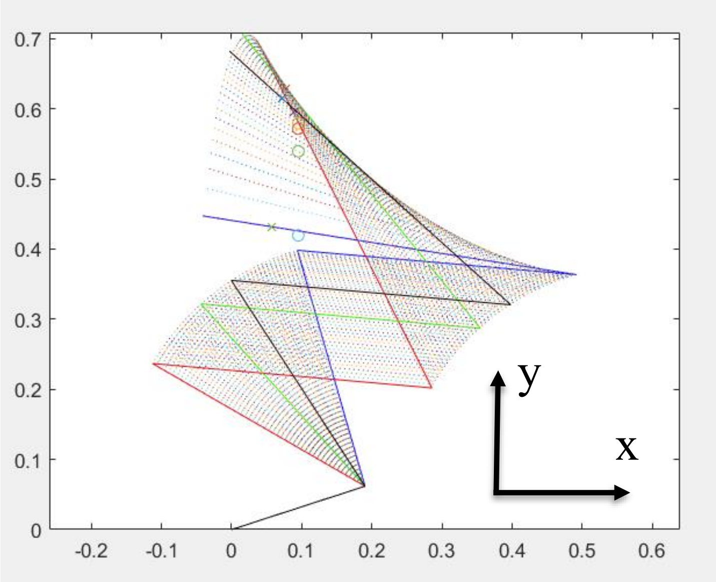
3.1.3 Criteria

To respect the IPF rulebook (International Powerlifting Federation, 2022), the lifter needs to reach a position with its upper leg under parallel, then, he has to extend his knees and hips to stand fully erected (upper leg vertical). As any downward movement is not permitted during the squat, the upper leg must increase its angle between the two extreme positions. Hence, the motion is conducted by the position of the upper leg, from under horizontal to vertical. The motion pattern can be described as the position of the body for each inclination of the upper leg.

Different criteria were first tested:

- Calculate the sum of the absolute joints torques and choose the smallest one for each inclination of the upper leg

Problem: Close to parallel ($\alpha_3 = 0\ °$) all the positions have the same sum of the absolute torques (Figure 12& Table 3)



Blue = Minimal weighted sum of the torques with a coefficient 2 at the knees

Red = Minimal weighted sum of the torques with a coefficient 2 at the hips

Black = Minimal standard deviation

Pink = Highest bar position

Figure 11 : Spectrum of the acceptable positions for the deepest squat position

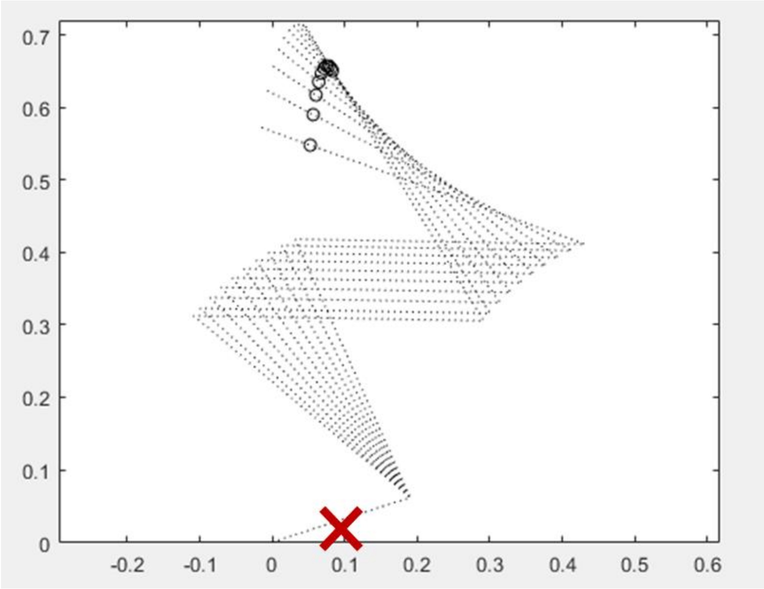


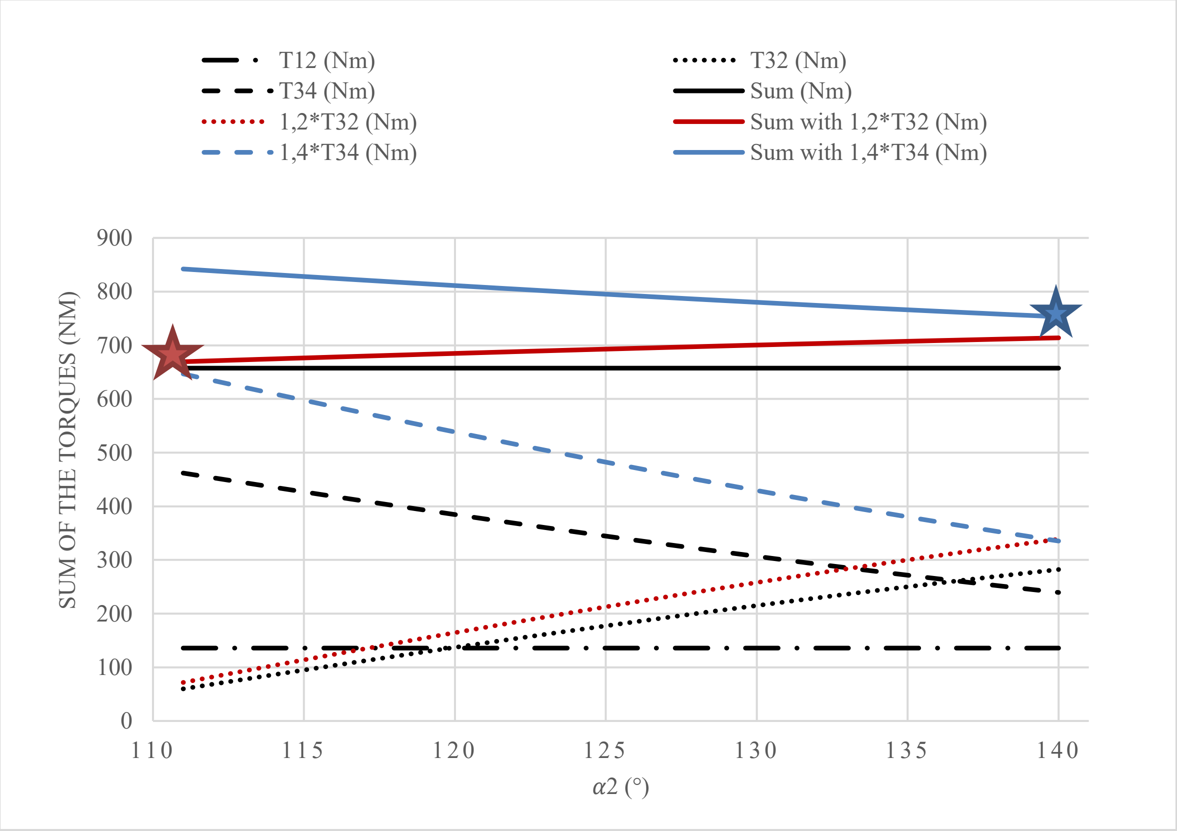
Figure 12 : Reachable positions for $\alpha_3 = 0°$

α_2 (°)	T_{12} (Nm)	T_{23} (Nm)	T_{34} (Nm)	*Sum of the absolute torques (Nm)*
111	135,750	-59,766	461,873	657,389
112	135,750	-68,626	453,013	657,389
113	135,750	-77,423	444,216	657,389
114	135,750	-86,155	435,484	657,389
115	135,750	-94,820	426,819	657,389
116	135,750	-103,414	418,225	657,389
117	135,750	-111,936	409,704	657,389
118	135,750	-120,382	401,258	657,389
119	135,750	-128,750	392,889	657,389
120	135,750	-137,037	384,602	657,389
121	135,750	-145,242	376,398	657,389
122	135,750	-153,360	368,279	657,389
123	135,750	-161,391	360,248	657,389
124	135,750	-169,331	352,308	657,389
125	135,750	-177,178	344,461	657,389
126	135,750	-184,930	336,709	657,389
127	135,750	-192,585	329,054	657,389
128	135,750	-200,139	321,500	657,389
129	135,750	-207,591	314,048	657,389
130	135,750	-214,938	306,701	657,389
131	135,750	-222,179	299,460	657,389
132	135,750	-229,310	292,329	657,389
133	135,750	-236,331	285,309	657,389
134	135,750	-243,238	278,402	657,389
135	135,750	-250,029	271,610	657,389
136	135,750	-256,703	264,936	657,389
137	135,750	-263,258	258,382	657,389
138	135,750	-269,690	251,949	657,389
139	135,750	-276,000	245,639	657,389
140	135,750	-282,184	239,455	657,389

Table 3 : Calculation of the joint torques for each reachable position

- Calculate the weighted sum of the joints torques with a different coefficient at knees and hips
    - Problem: Whatever the coefficients, the result is one end of the spectrum and no “in between” is reachable (Figure 13).

Figure 13 : Influence of the coefficients on the sum of the torques



- Choose the position with the smallest standard deviation between the hips and knees
- Choose the position where the bar is the highest for every inclination to reduce the potential energy

As no studies existed on the use of these criteria to optimize the motion, it was not possible to choose which one would led to the most efficient pattern.

Regarding the cost function, the fact is that, if the centre of pressure is above mid foot during the movement, all the reachable positions have the same sum of absolute torques (Table 3). Hence it was not possible to use this as an optimization criterion. The literature was studied and another criteria was looked for, the result was that many studies on sport performance use the energy as a cost function. Local and global approaches are possible, for our study, it was chosen to use a local one as the squat has the same beginning and ending position.

The French literature (Leboeuf, and Lacouture, 2008) provided us with a formula using a local energy approach that we decided to apply to all previously found trajectories.

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To calculate the energy consumed during the squat:

- Calculate the duration of the motion
    - The angular velocity of the thigh relative to the floor is considered constant throughout the lift
    - The smallest average velocity at which an athlete can lift a bar is considered 0,17 m/s based on collection of athletes training log (Table 4).

Number of squats collected	Number of powerlifters	Average Minimum Avg_Vel	Standard deviation
2700	6	0,17 m/s	0,045 m/s

Table 4 : Average velocity based on training log data (with consent)

- Calculate the time difference between two inclinations
- Calculate the absolute rotation speed of each segment
    - 1^{st} order derivative
- Calculate the relative rotation speed of each joint
    - Difference of two derivatives
- Calculate the absolute power value at each joint (torque * rotation speed)
- Calculate the sum of the power at each joint
- Integrate the result on all the motion to have the total energy cost

This calculus was applied on the feasible trajectories and here are the results

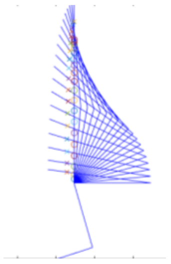
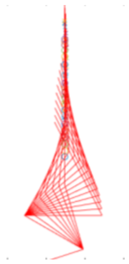
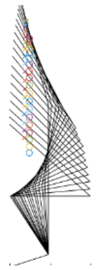
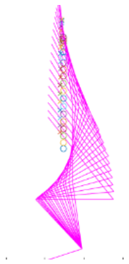
Kinogram				
Energy cost	2628 J	2018 J	2172 J	1976 J

Table 5 : Energy cost of different strategies

3.1.4 Validation of the model by comparison to standard dynamics analysis

As the model was purely mechanical, it was chosen to check the quasi-static hypothesis on ADAMS™ View software with a dynamic model before going further. To do so the following steps were used:

- Create as many points as necessary joints and align them on a horizontal line with the same distance as the previous model
- Create rigid body links between the points that would model the limbs
- Modify the CoM position of each body to put it at the same location as on the previous model
- Set the mass of each body to put the same as the model
- Create revolute joints between the rigid bodies
- Create a fix joint between the rigid body modelling the bar and the one modelling the trunk
- On Matlab, fit polynomes on the angle/time evolution of each articulation
- On Adams impose motion on the connectors
- On the result set of the post processor of Adams:
    - Plot the z-torque of each joint

- Plot the angle of each joint
- Derivate the curves of the angles
- Multiply the derivative and z-torque curve of each joint
- Change the curves into their absolute value
- Sum all the curves
- Integrate the sum

The result of this comparison showed a difference of less than 0.5% between the Matlab model and the Adams one which encouraged us to keep on using our Matlab model for further developments.

3.2 Optimization

As we thought, the trajectory minimizing the energy consumed was the one with the smallest difference in potential energy for the bar but, at this time, it is not possible to know if this trajectory is the most economical of all or not.

Hence, we faced on optimization problem. The possible positions for each depth being discretized, it is easily possible to calculate the number of trajectories. Between 45 and 61 positions were possible for each of the 96 depth angles, hence 61^{96}=2,46*10^{171} trajectories were possible. As our cost function took 0,00266s to calculate the energy of one trajectory, around 2,08*10^{161} years would be needed to find the optimal trajectory with an exact calculation.

Thus, it was needed to use an Evolutionary Algorithm to find the solution. In the papers from the literature which talk about optimization problem, genetic algorithms were used (Bobbert et al., 2016; Rahmati and Mallakzadeh, 2014). The choice was made to follow the same process for our model.

3.2.1 Initial population

It was chosen to initialize the population with 100 different cases.

To make sure the algorithm would not converge to a local minimum it was important to spread the parents across the surface. To do so a matrix C of size 100*2 was created with random integers from 1 to k (the number of α_{2_k} values). Another matrix D of sizes 100*j (the number of α_{3_j} values) was created with each line being the linear vector corresponding to C. E.g.: If C(1, :) =[2,8] than D(1, :) = [2,2,2,3,3…,8]. That way all the parents would be different every time the algorithm is run.

Once all the potential parents were created the following step was to evaluate the cost function for them and make sure none of them was an impossible trajectory. Both aspects were evaluated at the same time in an evaluation function detailed in the following paragraph.

3.2.2 Evaluation

That function was initialized with one line of D corresponding to the α_{3_j} sequence of one parent. Thanks to this sequence and the big data base of all the available positions it was possible to collect all the positions needed to execute this sequence.

From that positions the height of the bar at the beginning and end of the concentric phase of the lift were extracted. The difference between that two positions as well as the fixed velocity were used to calculate the total duration of the push as well as the time step between two consecutive positions.

Than the sub-matrixes containing the angles, torques and centre of mass positions of each position were extracted to calculate the cost function. If one of the positions was impossible the corresponding line in the moment and angle matrixes of the database would have been set as the null vector.

Before applying the cost function taken up in the literature (Leboeuf, and Lacouture, 2008) two key features needed to be extracted: the relative angular velocity of each joint as well as the actuator torque exerted by the segment Si-1 on Si. The first one was calculating by subtracting α_{i-1} to α_i for each joint and dividing the result by the time step. The second one was directly extracted from the torque matrix. and smoothed thanks to a polynomial fitting.

The two matrixes were multiplied term by term and the absolute values of each joint were then summed. The cost function is finally calculating by integrating that column vector.

At that point, the sequences were ranked based on their cost function (lowest cost function at the top of the ranking).

If some positions of the sequence were impossible, the previous mathematical operation on angles would create huge values on the angular velocity vector, hence also on the resulting matrix of the multiplication and the cost function. As a result, the sequences including impossible positions would be ranked at the bottom of the ranking and disappear after some iterations.

Equation 1 : Cost function (Leboeuf, and Lacouture, 2008)

$$W_2^b(F_{int}) = \int_{t_0}^{t_1} \sum_{i=2}^{4} \left| C_{i-1,i}^a(t).\Omega_{i,i-1}(t) \right| dt$$

With:

- $C_{i-1,i}^a$ the actuator torque exerted by the body i-1 on i,
- $\Omega_{i,i-1}$ the relative angular velocity of the body i compared to i-1

3.2.3 Next generation

For each loop, a weighted draw was performed between the parents to create the 100 crossover children. A higher probability was given to choose the parents with the lowest cost function. A random crossover coefficient between 0 and 1 was assigned to each pair so as not to always use half of each parent.

Then 34 parents were randomly selected for the mutation and a random mutation (inside a predetermined range) was assigned to each of them. It was then verified that they were still within the acceptable range of motion.

Once all the children were created, the cost function was applied to each of them and they were ranked with the parents. All the duplicates were removed and the top 100 individuals were chosen as new parents. The loop should be repeated a minimum of times and stopped after 15 iterations without improvement or when 500 iterations are reached.

At the end, the best individual was chosen.

3.2.4 Convergence and results

The convergence of this method was assessed by repeating the algorithm 10 times with different starting points and making sure the cost function decreases with time for all of them. It was also checked that the cost function of the results was within a range of 2,5% all 10 times.

The results of the 5 first repetitions are displayed in Table 6.

In addition, the results all consumed less energy than the previous best ones found in 3.1.3, which proves the effectiveness of the method. The results of the genetic algorithm will be presented and confronted to the experimental results in the Simulation vs experimentation section.

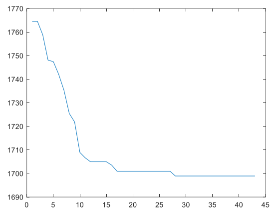
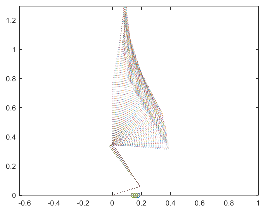
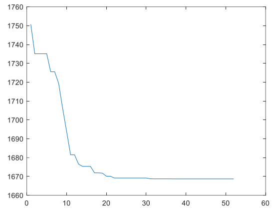
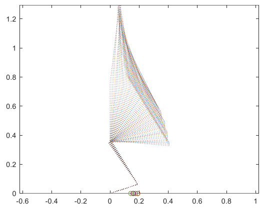
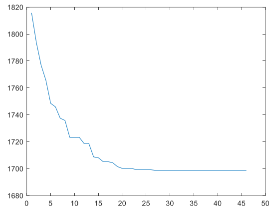
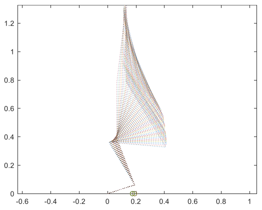
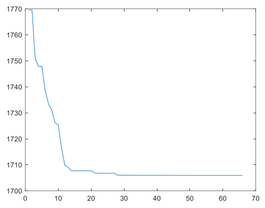
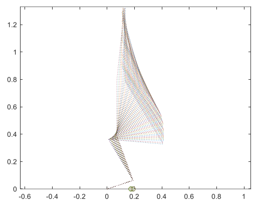
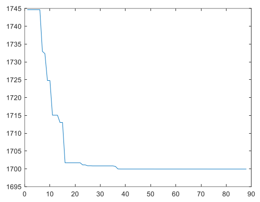
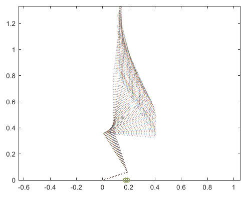
Energy Cost (J)	Evolution of the cost function (J) according to the number of iterations	Kinogram of the result
$1.6989^{e}03$		
$1.6687^{e}03$		
$1.6986^{e}03$		
$1.7059^{e}03$		
$1.6999^{e}03$		

Table 6 : Convergence test of the genetic algorithm

Chapter 4 Experimentation

4.1 Introduction

The state of art alights the fact the experiments on elite powerlifters is lacking as well as measurements in ecological conditions (Ferland and Comtois, 2019). In addition, most studies tried to measure the influence of changing one parameter -foot stance, bar height, shoes- (Glassbrook et al., 2019; Larsen et al., 2021a; Murawa et al., 2020; Swinton et al., 2012; Williams, 2015) rather than understanding the natural mechanics of the movement as well as the limiting factors, which is key for performance. The objective of this protocol is to capture the movement of the most experienced athletes possible in the most ecological situation possible in order to compare their movement with that of an optimized digital avatar and to criticize the hypotheses made on this avatar. The ultimate goal is to use a virtual avatar to optimize the sporting gesture of high-level athletes in order to reduce their risk of injury on the one hand and to increase their performance on the other.

Before going further into the subject, it seemed important to us to redefine what a squat is. The motion of the squat basically consists in a flexion extension of the lower limbs with a bar loaded as heavy as possible carried on the shoulders.

In order to help the reader better understand the rest of the protocol, here are some details on the choices made for the latter.

To better understand what are the strong and weak points of a lifter, one solution is to study in particular the sticking point and to look at the differences between a successful heavy lift, where the lifter has a marked sticking point but pulls through, and a failed lift. This type of study was only done once per (Flanagan et al., 2015) and the results support the hypothesis that different lifters do not have the same sticky region or the same strong and weak muscles. Even if it would have been very interesting to do the same thing on many subjects, the problem with this kind of experiment is that it is very tiring for the athletes because they have to produce a maximum effort 2 times, once for the maximum attempt and another for the supramax (failed) attempt. Usually, lifters train year-round on sub-maximal loads that they can do for reps to manage fatigue and be able to lift a sufficient workload volume per week. This is called work capacity, meaning the amount of work an athlete can train and recover from. Therefore, they rarely lift their one repetition maximum (1RM) in training so as not to get too tired and try to avoid failed lifts as they are very taxing on the central nervous system. As a result, forcing elite lifters into a protocol where they must attempt their 1RM and above could completely screw up their planning and make them more fatigued. Since fatigue is one of the main causes of injury (Gabbett, 2016), this type of experience cannot be imposed on athletes. One solution would be to use competition sequences. Powerlifting competitions are where lifters will try to lift the heaviest in squat, bench press and deadlift to build the highest possible total to beat their opponent by gender, age and weight class. Therefore, this is where failed attempts are most likely to occur if athletes and coaches have misjudged the athlete's true 1RM. Unfortunately, unlike weightlifting, where the athlete is alone with the bar on the platform, in powerlifting competitions, a support to hold the bar as well as three to five spotters and five referees are also on the platform (Figure 14). Moreover, the referees are also on the same platform. Therefore, it is difficult to find a place for the cameras where you have an overview of the lifters. This means that, even though it could be allowed, capturing the motion of the lifters using cameras and marker-less technology are more difficult to use in powerlifting than in weightlifting where it has been done a lot (Akkuş, 2012; Harbili, 2012; Ikeda et al., 2012; Nagao et al., 2019; Wang, X and Pylypko, V, 2009). For this reason, it would be very complicated to do squat experiments during powerlifting competitions. As a result, it was chosen to do the experiment in training

conditions.

Figure 14 : French lifter Amélie Mierger surrounded by spotters (Image : White Light Media, with permission)

As expressed in the state of art (2.3) intermediate and elite athletes often do not volunteer for studies because they follow special training planning all year round and cannot stop nor pause nor modify their program for a week or two to follow a scientific training protocol. Therefore, the best way to convince them to participate in a scientific study is to discuss the experience with the athlete and their trainer beforehand in order to integrate the experience into their planned training. Hence, to ensure a higher level of the volunteers than the average in the literature (Glassbrook et al., 2019; Hecker et al., 2019; McLaughlin et al., 1978; Swinton et al., 2012; van den Tillaar et al., 2020) it was decided to conduct the experiments during training camps and only set a minimum level of exertion using either the Rating of Perceived Exertion (RPE) (Balsalobre-Fernández et al., 2021; Ferland and Comtois, 2019; Halperin et al., 2021; Helms et al., 2018; Neto et al., 2021; Suchomel et al., 2021) or a percentage of the estimated maximum of one repetition (e1RM). The RPE scale used was the one created by Zourdos in 2016 (Zourdos et al., 2016) which is the one used daily by athletes in resistance training (Helms et al., 2016).

RPE Scale	
5,5	This set was too easy to grade
6	This was a warming up set for sure
6,5	This was maybe a warming up
7	I could have done 3 more reps for sure
7,5	I could maybe have done 3 more reps
8	I could have done 2 more reps for sure
8,5	I could maybe have done 2 more reps
9	I could have done 1 more rep for sure
	I could maybe have done 1 more rep
10	MAXIMAL effort

Table 7 : RPE Scale based on repetitions in reserve

Regarding the type of model to create it was decided to follow what had has already been done in the literature (Schoenfeld 2010; Hoover et al. 2006; Mastalerz et al. 2019; Nagao et al. 2019), it was chosen to model only the trunk, the thigh and the shank and work in 2D in the sagittal plane Figure 15.

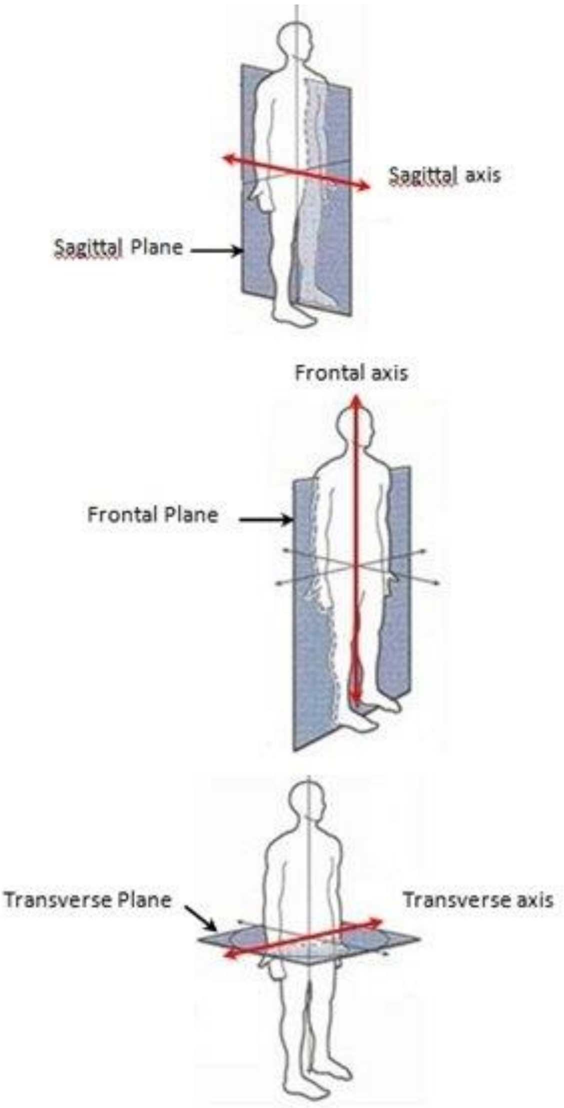


Figure 15 : Axes and planes of the human body (Balaşa et al., 2017)

Unlike for weightlifting movements, where the bar is held by the hands and can move relative to the body, for the squat movement the bar is held across the upper back of the athlete and is considered fixed relative to the spine. Therefore, the arm and upper arm do not need to be modelled. Also, to control the position of the centre of gravity in relation to the base of support, the foot segment has been added. To measure the motion of each segment in 2D, a reflective marker must be placed at each end of that segment, at the centre of the joint. To track movement of the feet, shank, thigh and trunk, literature was used (Tunstall and Shah, 2018) and the bony chosen landmarks were: 5th metatarsal, malleolus, lateral knee condyle, greater trochanter and 7th cervical vertebra. In case we want to check back stiffness later, more markers have been added on the 1st and 5th lumbar vertebra. Finally, a marker was fixed on the bar to check its position in relation to the 7th vertebra. In powerlifting, the bar can be held anywhere on the shoulders (International Powerlifting Federation, 2022) and depending on its position Figure 16 the lever arm to the hips as well as the motor strategy of the athlete will be different. For this reason, it is important to check this distance during experiments, even if for "high bar" lifters, the two landmarks of the 7th cervical vertebra and that of the bar can be confused on the acquisitions.

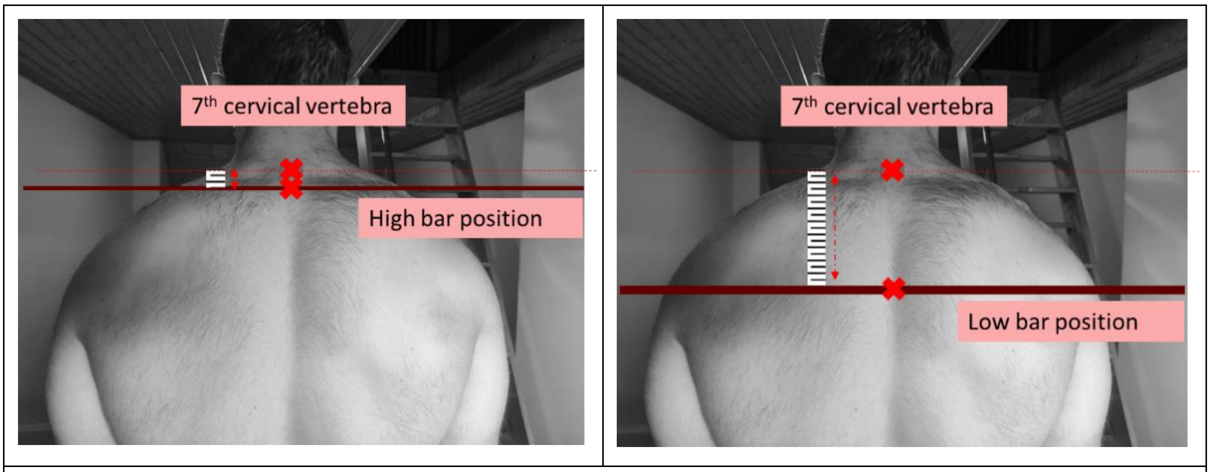


Figure 16 : Different bar positions seen in powerlifting (with permission)

4.2 Material and methods:

4.2.1 Assumptions

The idea we had was that when we record how elite athletes move during their regular training routines, we can observe their most natural movement patterns. We assumed that when they're in their usual training settings, they would move the way they are most comfortable and used to moving. This helps us get a better understanding of how their bodies naturally work during lifting

We had several important things we wanted to achieve in with this experiment:

- Creating a personalized avatar: Our first goal was to gather information about people's body measurements, like their height and body proportions. We wanted to use this information to design a special computer-generated avatar that would look like each individual person. We planned to optimize the lifting pattern of this avatar to make it the best possible at squatting.
- Testing simulation ideas: Our second goal was to check if the ideas we put into our computer simulation were correct. We wondered if certain things we thought would happen in the simulation would actually happen when real people did the movements. In that case, we wanted to see if the Centre of Pressure stayed still under the middle of the feet during the squat, and if the thigh would move at a constant speed.
- Extract key biomechanical data: Our third goal was to get some important information about how the body works during the movements. We wanted to find out how much force each joint of the body could create. We also wanted to track the way the body's joints move over time thanks to a kinogram, kind of like a picture of how the lifter moves. Then, we planned to compare this data from elite lifters with what our simulation predicted.

Powerlifting material

Lifting material:

- A powerlifting bar (the bar shall weight 20kg, diameter 29mm, total overall length 2.2m (International Powerlifting Federation, 2022))
- Calibrated powerlifting plates (“All discs used in competition must weigh within 0.25 percent or 10 grams of their face value. The diameter of the largest discs shall not be more than 45 cm. The hole size in the middle of the disc must not exceed 53 mm or be less than 52mm.(International Powerlifting Federation, 2022))
- Squat stands or squat cage or combo rack (no monolift) as shown on Figure 17. This choice was made because part of the squat movement in competition consists in unracking the bar from its support and walking back to put itself into the starting position. Unfortunately, the monolift support suppresses the walkout part of the lift.
- Calibrated (weighing 2.5kg each) (Figure 18)

	
a. Combo rack Eleiko™ IPF Competition Combo Rack	b. Squat cage Rogue™ Squat Cage

	
c. Squat stands Powergym™ Squat Stands	d. Monolift Elitefts™ Monolift

Figure 17: Different types of squat supports

	Figure 18 : Collars

Personal Equipment:

- Shoes “Shoes shall be taken to include only indoor sports shoes/sports boots […] Hiking boots do not fall into this category. No part of the underside shall be higher than 5 cm.” (International Powerlifting Federation, 2022)
- Optional:
    - Knee sleeves “Knee sleeves shall be of a maximum thickness of 7 mm and a maximum length of 30 cm. The sleeves must be constructed entirely of a single ply of neoprene, or predominantly of a single ply of neoprene plus a

non-supportive single layer of fabric over the neoprene" (International Powerlifting Federation, 2022)

- Powerlifting Belt "The main body shall be made of leather, vinyl or other similar non-stretch material […] Width of belt maximum 10 cm. Thickness of belt maximum 13 mm along the main length."(International Powerlifting Federation, 2022)
- Wrist Wraps "Wrists wraps shall not exceed 1 m in length and 8 cm in width. Any sleeves and Velcro patches/tabs for securing must be incorporated within the one-meter length. A loop may be attached as an aid to securing". (International Powerlifting Federation, 2022)

		
Knee sleeves	Belt	Wrist Wraps
		
Flat shoes	Drop shoes	

Table 8 : Powerlifting equipment

4.2.2 Scientific material

The position of the joints was acquired using the Optitrack motion capture system. As the OMS technology was already available in the laboratory with several Flex 13 Optitrack^{TM} cameras, it was chosen as the preferred technology. In addition, it was chosen to have a Bertec^{TM} portable force plate to measure the position of the centre of pressure as well as the force vector.

4.2.2.1 Principle of operation

OptiTrack is a motion capture system used to track the movement of objects or subjects in a three-dimensional space. It is commonly used in various fields, including animation, biomechanics, virtual reality, robotics, and video game development. Here's how OptiTrack works:

1- Marker-Based System: OptiTrack uses a marker-based approach, where reflective markers are placed on the objects or subjects to be tracked. These markers reflect infrared light emitted by cameras, making them visible to the system.

2- Camera Setup: OptiTrack consists of multiple infrared cameras strategically positioned around the capture area. These cameras work together to capture the movement of the markers.

3- Calibration: Before tracking can begin, a calibration process is required to determine the position and orientation of each camera relative to the others. Calibration involves placing a known pattern (usually a rigid calibration wand or a calibration square) in the capture area, and the system uses the reflections from the markers on the pattern to calculate the camera's position and orientation.

4- Marker Tracking: Once the system is calibrated, it can begin tracking the markers in real-time. As the markers move, the cameras detect their positions by analyzing the reflected infrared light. The system then triangulates the 3D position of each marker based on the information received from multiple cameras observing the same marker.

5- Data Processing: The tracked 3D positions of the markers are sent to a computer where specialized software processes the data in real-time. The software applies filtering and smoothing algorithms to improve the accuracy of the tracking data and reduce noise.

6- Skeleton Reconstruction (Optional): In applications involving human motion capture, the tracked markers can be used to reconstruct a virtual skeleton. The skeleton can then drive a 3D model or character, allowing for real-time animation.

7- Data Output: The processed tracking data can be exported in various formats, depending on the application's requirements. It can be used in animation software, biomechanics analysis tools, or directly integrated into interactive applications like virtual reality experiences or video games.

A Bertec force plate is a specialized piece of equipment used for measuring ground reaction forces and moments in biomechanical and biomechanics research. It is commonly used in fields such as gait analysis, sports science, and clinical assessments. The principle of operation of a Bertec force plate involves several key components and concepts:

1- Load Cells: A Bertec force plate consists of multiple load cells, which are sensors that can measure the force applied to them. These load cells are strategically positioned within the force plate to accurately capture the forces exerted by a person or object standing or moving on the plate.

2- Strain Gauges: Load cells typically contain strain gauges that are bonded to them. These strain gauges are sensitive to changes in electrical resistance caused by deformation of the load cell when a force is applied. When force is applied to the force plate, the strain gauges change resistance proportionally, and this change is used to calculate the force being applied.

3- Calibration: Before using a Bertec force plate, it needs to be calibrated. Calibration involves applying known forces to the plate and measuring the corresponding electrical outputs from the strain gauges. This calibration process establishes a relationship between the electrical outputs and the actual forces.

4- Data Collection and Processing: When a person or object stands or moves on the force plate, the load cells measure the forces exerted in different directions (vertical, anterior-posterior, and medial-lateral) as well as the moments (torques) around these axes. The signals from the load cells are collected and processed by the force plate's electronics to provide real-time data on the magnitudes and directions of the forces and moments.

5- Coordinate System: Force plates typically use a specific coordinate system to represent the forces and moments. The vertical axis is commonly referred to as the Z-axis, while the anterior-posterior and medial-lateral axes are the X and Y axes, respectively.

6- Output: The force plate provides numerical data output in terms of force (in Newtons) and moment (in Newton-meters) values along the different axes. This data can be used to analyze various aspects of movement, such as gait patterns, balance, weight distribution, and joint loading.

4.2.2.2 Precision

Before starting any movement acquisition the validity and reliability of the OptitrackTM cameras was assessed. To do so, the system was calibrated according to the manufacturer's protocol to obtain “high precision”. Then, only 2 markers were fixed on the wand at a distance of 50,0 mm, measured with an electronic digital calliper (Figure 19). Five sequences were then captured in which the user moved the wand around the calibrated area. The 3D data of the position of the 2 markers were then exported as a c3d file. Finally, Matlab^{TM} was used to import the data and calculate the distance between the markers at each frame and compare it to the actual distance of 50,0mm. Table 9 shows the difference between the motion capture measurement and the distance between the two markers attached to the wand measured by the calliper. Since the distance is fixed, measuring a Pearson correlation coefficient or an ordinary regression of the least product would have made no sense. Therefore, only the mean and maximum difference as well as the standard deviation per test session were calculated. As the precision of the cameras is more than 10 times better then the potential errors due to the positioning of the markers on the bony landmarks (Begon and Lacouture, 2005), it can be considered as a valid acquisition tool.

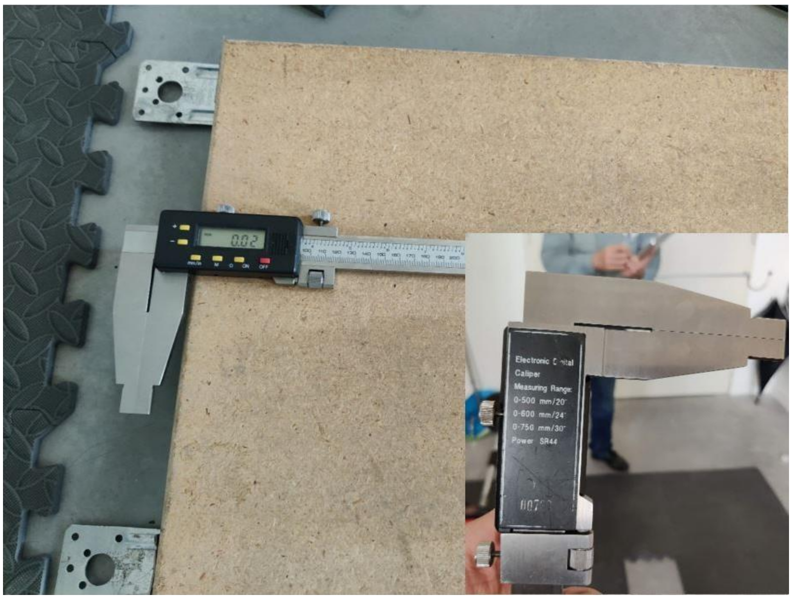


Figure 19 : Electronic digital calliper

Session	**Max difference (m)**	**Mean difference (m)**	**Standard Deviation (m)**
1	0,00410	0,00019	0,00028
2	0,00280	0,00032	0,00039
3	0,00150	0,00022	0,00017
4	0,00580	0,00029	0,00051
5	0,00770	0,00017	0,00024
6	0,00560	0,00020	0,00029
Total	*0,00770*	*0,00023*	*0,00031*

Table 9 : Validity of the Optitrack^{TM}cameras

4.3 Protocol and acquisitions

4.3.1 Cohort

CERSTAPS authorization was obtained on 12/15/2021 and is available in annexe 7.2.

The 2 subjects were recruited among the members of the French Powerlifting team. The condition of inclusion was an experience of at least 1 year at the international level in IPF classic powerlifting. The condition of participation was the realization of at least one repetition of competition type squat at a load corresponding to at least 75% of the e1RM or a 7 RPE which is considered moderate effort. If they met the criteria, they were welcome to participate in the experience.

Volunteer	A	B
Sex	Feminine	Masculine
Age	19	21
Size	160cm	185cm
Bodyweight	70kg	110kg
Squat 1RM	160kg	300kg
Experience	World Champion Junior Category (IPF – classic)	World Champion Junior Category (IPF – classic)

Squat type	Low bar back squat	Low bar back squat
Type of shoes	Romaleos 4	Romaleos 4
Knee Sleeves	Yes	Yes
Belt	Yes	Yes
Wrist Wraps	Yes	Yes

4.3.2 Parameters studied

Studying the centre of pressure (CoP) position, maximal torque at each joint, and the velocity of the thigh during the concentric phase of the squat motion is crucial for a comprehensive understanding of the biomechanics and motor control involved in this fundamental movement. The CoP position provides insights into how an individual distributes their weight over the feet, reflecting balance and weight shift dynamics. Analysing the maximal torque at each joint offers valuable information about muscle activation patterns and joint loading, helping to identify potential sources of strain or inefficiencies. Meanwhile, the velocity of the thigh during the concentric phase sheds light on the speed and coordination of the movement, impacting the effectiveness and efficiency of the squat. By examining these interrelated factors, researchers and practitioners can gain a holistic view of the biomechanical and neuromuscular strategies employed by individuals during squatting. This knowledge is invaluable for optimizing performance, reducing injury risk, and designing targeted training and rehabilitation protocols tailored to each individual's unique movement characteristics.

4.3.3 Conduct of the experiment

The experiment took place at CREPS in Vichy, the national powerlifting training center of the FFForce. This CREPS has in particular accommodation and catering. Thus, it is considered that the fatigue linked to the displacement at the CREPS is negligible.

In order to have conditions as ecological as possible and not to disturb the athletes, only one subject was evaluated per session. Even if the experiments would be longer due to the early occupation of the force plate, the choice was made to do the squat warm-up on the force plate and with the reflective markers so that the athlete is not disturbed by the floor change or presence of the markers. Also, the synchronization of the force plate and cameras could be tested during warm-up sets to make sure everything is working well.

A contact made it possible to establish a day and an hour of experimentation corresponding to a session planned by the athlete.

Prior to the experiment, the motion capture equipment – cameras and force platform – was installed and calibrated in the training room. Because the force plate is 40 cm x 60 cm, some lifters squatting with a large stance could not put both feet on the force plate. To circumvent this problem, a second plate of the same height was made of wood and fixed to the supports of the force plate. Therefore, all lifters would be able to put one foot on each plate and both would not move if a lateral force was applied. Also, since the athlete has to step back from the rack to squat and the force plate is 4cm high, it would require athletes to step on it with a loaded bar on their back, which can be dangerous. So, fitness floor tiles or other materials of the same height were added under the loaded bar to even out the floor at the force plate. A possible experimental setup can be seen on (Figure 20)

Figure 20 : Lifting experimental setup

The athlete was welcomed in the CREPS training room in Vichy and the protocol was explained to him again, the equipment used for the experimentation detailed above was competition-type equipment with which the athletes were familiar. Likewise, the personal equipment of the athlete was left to his discretion provided that only accessories authorized in powerlifting competition and approved by the IPF were used. – squat shoes, knee sleeves, lifting belt, wrist wraps.

- the cardiovascular and articular warm-ups were left to the athlete's freedom
- once the athlete was ready to begin his squat session, he was fitted with passive reflective markers on the bony landmarks cited in section 3.2.1. Also, to be more precise with the cameras, as the movement was chosen to be studied in 2D, only the side with the foot on the force plate was fitted with passive markers and filmed, so that more cameras could see each joint marker.
- the athlete was asked to follow two instructions during the squat warm up : wait for the kick before unracking the weight and remain motionless on the force-plate for two seconds once his set is finished before putting the weight back on the rack. The second instruction was added because, when athletes know they are doing the last repetition of a set, they tend to step forward to rack the bar before finishing the lift or at the same time they finish. That movement was forbidden because it modifies the effort in the joints as well as the position of the centre of pressure. As the last repetition of the set is, most of the time, the hardest due to fatigue and time under tension, it is the most interesting to study. Yet, if athletes do not complete the last rep because they are stepping to rerack the bar, differences in joint loading and centre of pressure could be attributed to fatigue as much as to anticipated stepping motion.
- the athlete would warm up on the force plate and with the reflective markers accordingly to his usual routine respecting a rest period of 3 to 8 minutes between sets.
- the synchronization of the force plate and cameras could be tested during warm-up sets to make sure everything is working well.

The steps required for motion capture are as follows:

- the athlete's body weight and the weight of the loaded bar were noted

- The bar was loaded on the rack with a passive marker fixed in the centre

- The athlete place himself under the bar so that it is held horizontally on the shoulders

    o Acquisitions of cameras and force platforms are launched

    - A helper hits the platform with a reflective marker attached to his heel and leaves

- The athlete removes the bar from the rack and steps back to have his feet on the same line with the left one on the force plate

- Once stationary in the starting position, the athlete should begin to bend the knees and hips "until the upper surface of the legs at the hip joint is lower than the top of the knees" (International Powerlifting Federation 2022).

- The athlete should then extend the knees and hips to until he is motionless in an upright position with the knees locked

- The two previous operations are repeated for as many repetitions as prescribed in the athlete's program

- At the end of the last repetition, the camera and force platform acquisitions are stopped

- The athlete can rerack the bar

Depending on the lifter squat session, one or more acquisitions may take place, following the same steps.

Finally, once the acquisitions were completed, the passive markers were removed from the subject.

4.4 Results

4.4.1 Motive pre-processing

Once the acquisitions have been made, there are a few steps to follow before one can analyse the results.

The first is the cleaning of data acquired on the Optitrack^{TM} software itself. As no skeleton reconstruction model was used on it, the labelling part had to be done manually. To do this, the operator first had to merge the data corresponding to different temporal acquisitions of the same marker. If the field of view is hidden from a camera for even a tenth of a second, recording stops and another unlabelled marker is created when the field of view is regained. This process highlights the importance of placing the cameras at strategic positions before calibration, to ensure that two or more cameras would see each marker all the time, to save time during the labelling process and increase the accuracy.

In fact, when different acquisitions are merged, there are often empty spaces left, but to plot curves based on the data, these spaces must be filled. This option exists on Motive^{TM} and the software can fill in the blanks with linear or cubic curves with other parameters chosen by the operator. Although this option is very useful, it remains an approximation and not the reality, which further reinforces the importance of avoiding this situation as much as possible.

As soon as a single complete acquisition corresponds to each marker, they are labelled manually and the others, the interferences, are removed. Then the .c3d files are exported.

4.4.2 Matlab processing

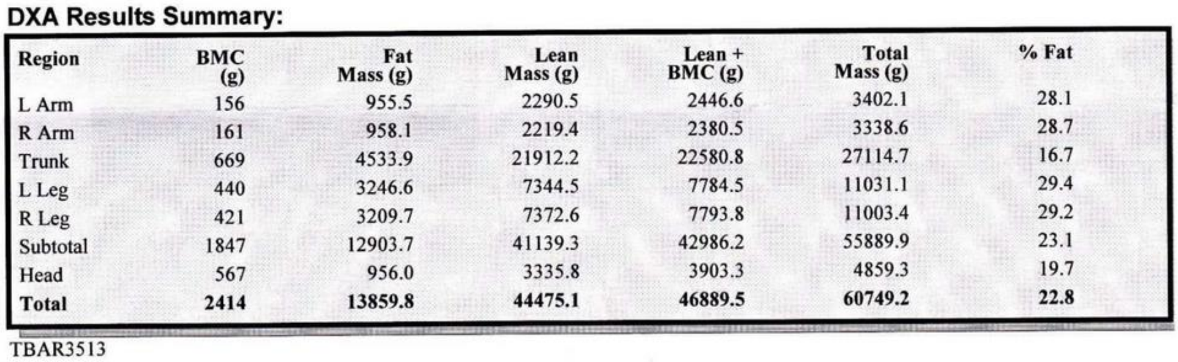
The goal was to process the data such that each lifter could be compared with his avatar (Figure 21) and the results of both the experimentation and the modelization had the same units.

A special library exists on Matlab^{TM} called BTK and was designed to read .c3d motion capture files. Thanks to the point label, the 2D coordinates of each marker in the sagittal plane Figure 15 were extracted as well as the analogue frequency. The heel strike, called a “tap”, was recognized manually and all acquisitions were cut off to start at this point. Next, the coordinates of the mark located at the front of the foot were chosen as the origin and all the other coordinates were modified accordingly. The next step was to calculate the length of the limbs. As indicated above, this was done in 2D by calculating the average distance between the two markers of each limb during the acquisitions Table 10.

First Marker		Second Marker		Corresponding segment
Experiment	Model	Experiment	Model	
5th metatarsal	O_1	Malleolus	O_2	Foot
Malleolus	O_2	Lateral knee condyle	O_3	Shank
Lateral knee condyle	O_3	Greater trochanter	O_4	Thigh
Greater trochanter	O_4	7th cervical vertebra	O_5	Trunk
Bar centre	G_b			Bar

Table 10 : Experimental marker position and model corresponding name

Other anatomical determinants such as the position of the centre of mass of each segment were calculated by applying literature references of Table 12 to experimental data. The distribution of body mass on each segment was reproduced from the DXA results of a female athlete in powerlifting (Table 11). Once all the data had been extracted and stored in structures, the mechanical calculation could begin.

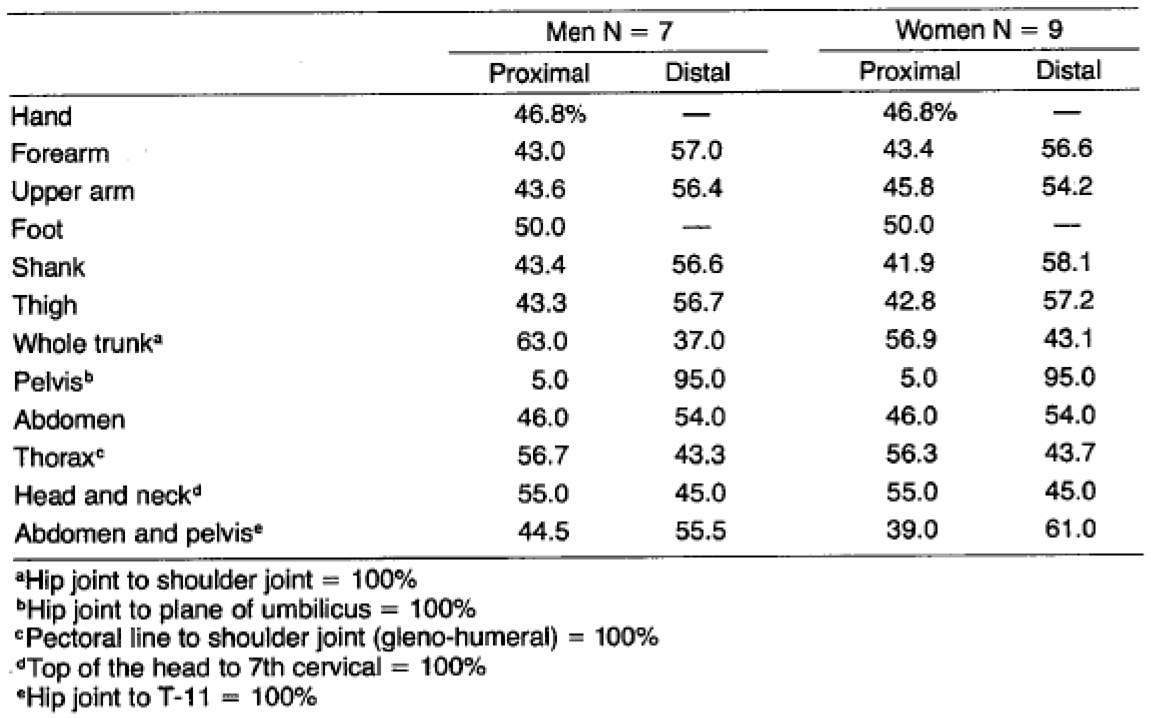


DXA Results Summary:

Region	BMC (g)	Fat Mass (g)	Lean Mass (g)	Lean + BMC (g)	Total Mass (g)	% Fat
L Arm	156	955.5	2290.5	2446.6	3402.1	28.1
R Arm	161	958.1	2219.4	2380.5	3338.6	28.7
Trunk	669	4533.9	21912.2	22580.8	27114.7	16.7
L Leg	440	3246.6	7344.5	7784.5	11031.1	29.4
R Leg	421	3209.7	7372.6	7793.8	11003.4	29.2
Subtotal	1847	12903.7	41139.3	42986.2	55889.9	23.1
Head	567	956.0	3335.8	3903.3	4859.3	19.7
Total	**2414**	**13859.8**	**44475.1**	**46889.5**	**60749.2**	**22.8**

TBAR3513

Table 11 : DXA results of a female powerlifter (with permission)



	Men N = 7		Women N = 9	
	Proximal	Distal	Proximal	Distal
Hand	46.8%	—	46.8%	—
Forearm	43.0	57.0	43.4	56.6
Upper arm	43.6	56.4	45.8	54.2
Foot	50.0	—	50.0	—
Shank	43.4	56.6	41.9	58.1
Thigh	43.3	56.7	42.8	57.2
Whole trunk[a]	63.0	37.0	56.9	43.1
Pelvis[b]	5.0	95.0	5.0	95.0
Abdomen	46.0	54.0	46.0	54.0
Thorax[c]	56.7	43.3	56.3	43.7
Head and neck[d]	55.0	45.0	55.0	45.0
Abdomen and pelvis[e]	44.5	55.5	39.0	61.0

[a] Hip joint to shoulder joint = 100%
[b] Hip joint to plane of umbilicus = 100%
[c] Pectoral line to shoulder joint (gleno-humeral) = 100%
[d] Top of the head to 7th cervical = 100%
[e] Hip joint to T-11 = 100%

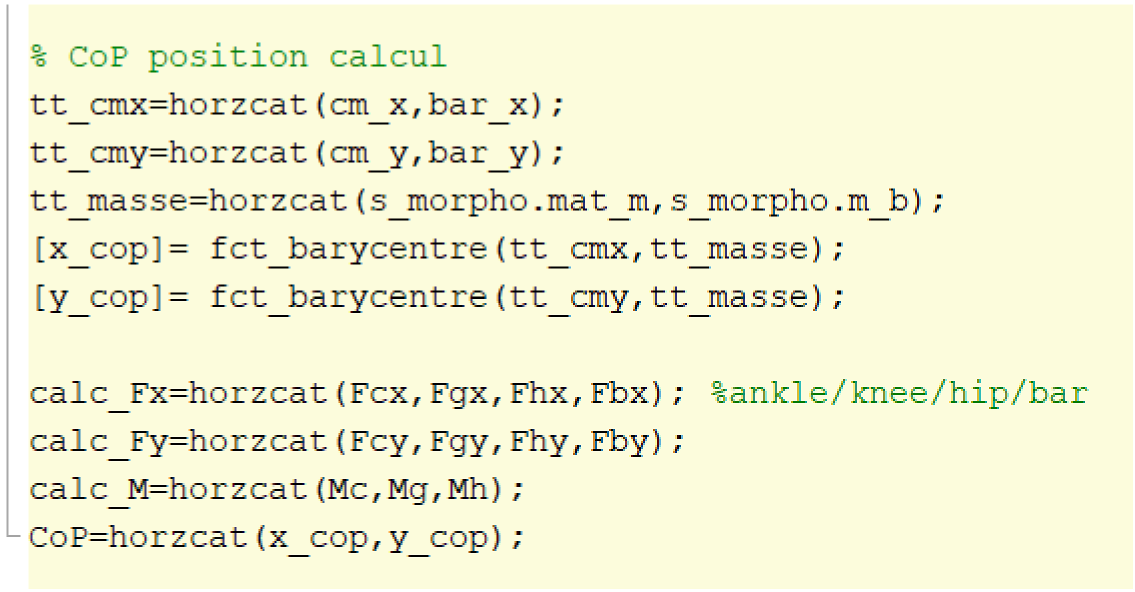
Table 12 : Location of the Segment Center of Gravity, as a Percentage of the segment Length (Plagenhoef, 1983)

Matlab Processing

Concerning the experimentation data

- Collect the data from the Optitrack™ cameras with the positions of the successive joints (toe, ankle, knee, hip, 7th cervical and bar) during all the acquisition
- Use the vertical position of the hip to identify the different phases of the movement and cut the data to only have the ascending part of the squat.
- Calculate the morphological parameters of the subject thanks to the relative position of the joints captured by the cameras and the masses of the subject and the bar collected during the experimentation.
- Calculate the position of the bar relative to the 7th cervical vertebra.
- Create a time scale using the acquisition frequency of the cameras
- Add the morphological data – masses and CoM positions – and use the principles of statics to calculate the torques at each joint during the lift (Table 2).

- Calculate the energy dissipation using the local approach (Leboeuf, and Lacouture, 2008)
- Finally, the position of the centre of pressure (COP) was calculated. Even though we had a force plate it was decided to use in this study the calculated CoP position so that people could replicate the protocol with less scientific equipment.



```
% CoP position calcul
tt_cmx=horzcat(cm_x,bar_x);
tt_cmy=horzcat(cm_y,bar_y);
tt_masse=horzcat(s_morpho.mat_m,s_morpho.m_b);
[x_cop]= fct_barycentre(tt_cmx,tt_masse);
[y_cop]= fct_barycentre(tt_cmy,tt_masse);

calc_Fx=horzcat(Fcx,Fgx,Fhx,Fbx); %ankle/knee/hip/bar
calc_Fy=horzcat(Fcy,Fgy,Fhy,Fby);
calc_M=horzcat(Mc,Mg,Mh);
CoP=horzcat(x_cop,y_cop);
```

Equation 2 : CoP position calculus

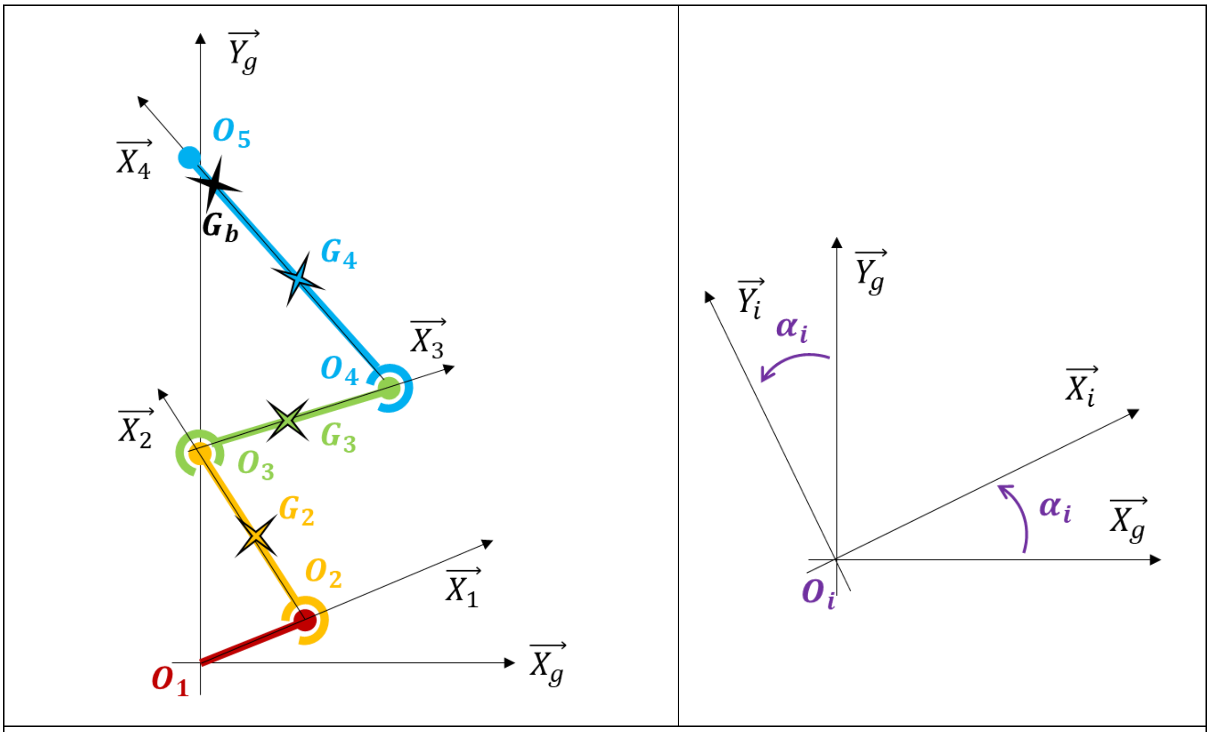


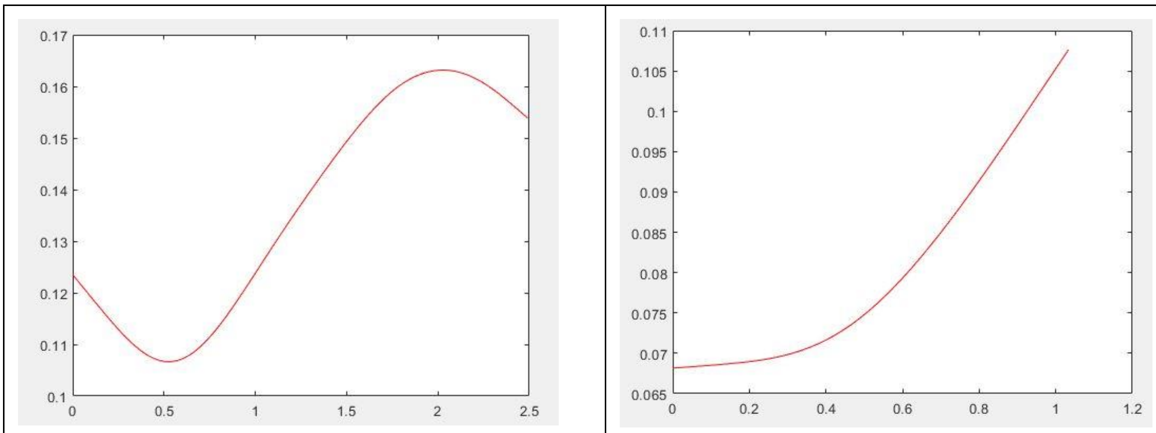
Figure 21 : Kinematic diagram of the mechanical model

4.4.3 Experimental results

As explained above the results extracted from the experiment were, on the concentric phase, the CoP position and more precisely the distance between the front of the foot and the calculated CoP, the maximal torque on each joint, the angular velocity of the thighs, all calculated from the marker position and the load data. All results are displayed on Table 13, Figure 22 and Figure 23.

Even though they have different shapes, both graphs of Figure 22 show a CoP position variating of up to 5cm during the concentric part of the lift. In addition, both CoP tend to move from a front position to a rear one during the squat. The result of this experiment suggest that the CoP position varies of several centimetres during the concentric phase. Its motion under the feet goes from front to back for both athletes.

Regarding the torque distribution both athletes tend to solicit more their knee than their hip and finally use their ankle. The thigh angular velocity of both subjects is displayed in Figure 23 and variations of more than 30deg/s can be seen on both figures.



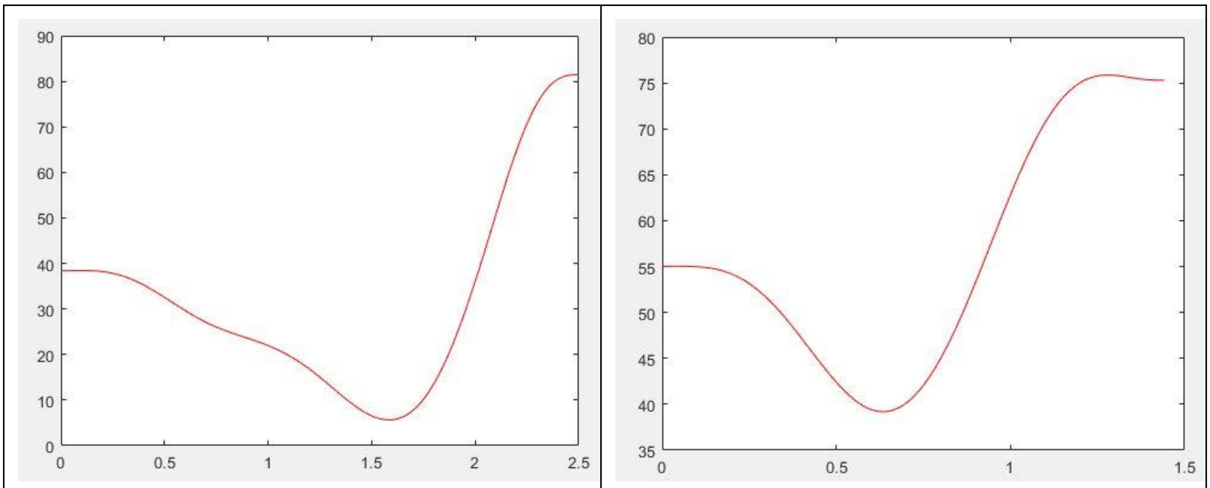
Male

Female

Figure 22 : Distance between the front of the foot and the CoP (m) depending on time (s) calculated from the marker position.

	Experimental maximal ankle torque	Experimental maximal knee torque	Experimental maximal hip torque
Male	963 Nm	2047 Nm	1576 Nm
Female	557 Nm	785 Nm	930 Nm

Table 13 : Experimental maximal torques



Male

Female

Figure 23: Angular velocity of the thigh (deg/s) depending on time from calculated from the marker position

4.5 Discussion

As expressed above this experiment was both exploratory research and a model calibration one. In those cases where the goal is to generate hypotheses or identify potential areas of interest, a small sample can provide preliminary insights that guide the direction of future studies with larger samples. Furthermore, when calibrating a simulation model to match specific experimental data, using a small sample can help fine-tune the model parameters. It's however important to note that the results should be interpreted with caution as only 2 elite subjects were studied.

First the variation in Centre of Pressure (CoP) position by several centimetres provides crucial insight into the complexity of the biomechanical system involved in the squat motion. This variation indicates that there are underlying degrees of freedom within the system that are not adequately captured by the existing model. The squat motion involves intricate interactions between various joints, muscles, and forces. The significant variation in CoP position suggests that there are subtle adjustments and movements occurring within the athletes' bodies that are not currently accounted for in the model. These unexplained variations indicate the presence of additional factors that influence the motion, and adding degrees of freedom can help capture these nuances. The CoP position provides insights into the body's stability and balance control mechanisms during the squat. The variation in CoP indicates that the body is continuously adjusting its position to maintain stability and optimize force distribution. Adding degrees of freedom to the model can help simulate these subtle adjustments and enhance the model's ability to capture the dynamic stability aspect of the squat. By incorporating additional degrees of freedom, the model can better mimic the complex interactions observed in the experimental data. This refinement allows for a more accurate representation of the real-world squat motion and provides a platform for studying and understanding the underlying biomechanics with higher fidelity. As a result, it was decided to had a degree of freedom on the model.

The hypothesis was made that the CoP position of the simulation will have the same movement tendency – from front to back. The same assumption was made regarding the repartition of the maximal torque on each joint. As the model was driven by the thigh motion considered constant it was expected that there would be some differences between simulation and experiment that could be calculated thanks to the values of Figure 28

Hence the next step is to compare the experimental data with the simulation one and discuss the results.

Chapter 5 Simulation vs experimentation

5.1 Need for model updating

To develop the model and run the simulations, many hypotheses were stated. One of the hypotheses of the first simulation was that the Centre of Pressure (CoP) of the system {athlete + bar} stays under mid foot during all the movement. This assumption was made because it is a common "cue" given to athletes. In general, in powerlifting, athletes are told to use their feet as a tripod (big toe, small toe and heel) and try to keep their CoP in the middle of these 3 points (Figure 24).

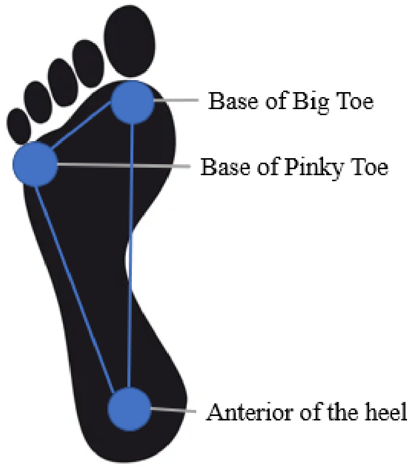


Figure 24 : The tripod foot

Figure 25: Zones of the foot

However, the results of the experiment showed that the CoP is located below the heel before the beginning of the squat, moves toward the ball of the foot (Figure 25) during the eccentric phase and back to the heel zone during the concentric phase. Because this pattern was the same on both athletes, it was decided to add a degree of freedom to the model regarding the position of the Centre of Pressure under the foot.

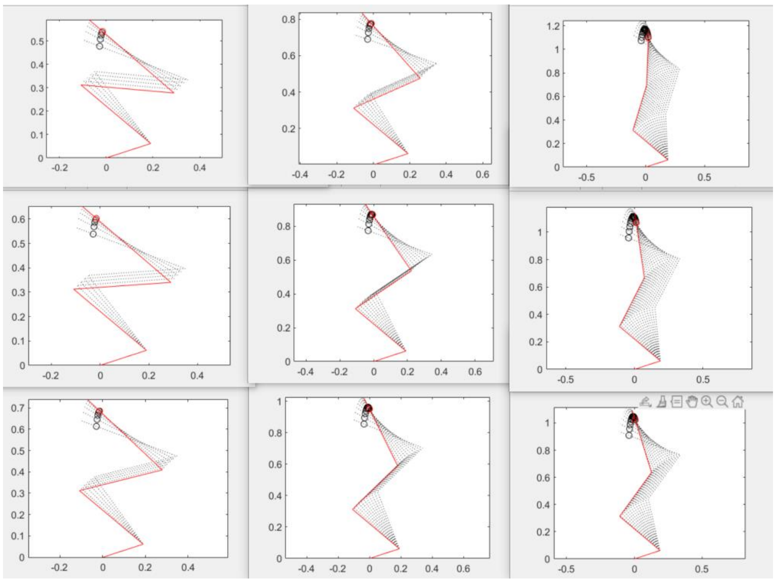
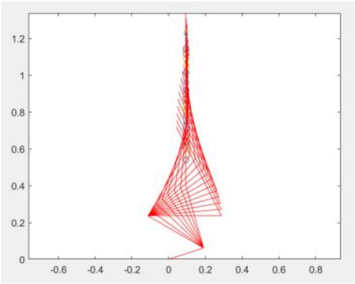
That degree was added by splitting the base of support into 12 acceptable positions, hence multiplying but 12 the time needed to calculate all the acceptable positions and the optimal pattern.

5.2 Fitting the simulation to the experimentation

To be able to compare the results of the genetic algorithm simulation from those of the experient, the first step was to process the data so they had the same format. All the coding was once again done with Matlab^{TM}.

Here are listed the steps to follow to fit the simulation model parameters to the experimental data:

- Set the morphological parameters of the model thanks to the data extracted from the experimentation
    - Distance between the bar and the 7th cervical vertebra set the position of the bar
    - Average distance between the joints during the acquisition for a subject as the length of each body for that subject (Begon and Lacouture, 2005)
    - Mass of the bar
    - Mass of the subject distributed on each body conforming to a previous DXA result of a French powerlifter, as in the Chapter modelization
    - Range of motion of the inclination of the thigh (3) relative to the floor (α_3) see Table 3
    - Duration of the concentric part of the squat
- Calculate all the eligible positions for the personalized model and store them into a dedicated data structure (Figure 26).
- Let the genetic algorithm calculate a theoretical optimal trajectory
- Store the following results from the genetic algorithm calculus:
    - Positions of the joints
    - Bar position
    - Centre of Pressure position of the full system
    - Energy dissipation value
    - Inclination of the thigh relative to the floor
    - Time scale
    - Angles of the different bodies relative to the floor
    - Torques at each joint during the lift

	
Some of the eligible positions stored in the structure (On each figure $\alpha_3 = cte$)	One trajectory (On one figure -5°< $\alpha_3 <$ 90°)
Figure 26: Positions vs trajectory	

5.3 Results

Once the same data were available both from the genetic algorithm calculus as well as the experimentation, it was possible to compare.

On the model, the assumption was made that the thigh angular velocity was constant from the beginning till the end of the concentric phase. During the experimentations, as the Figure 23 shows, we noticed that this velocity decreases until a “sticking point” is reached and then increases. The location of this sticking point or region can be seen by the change of darkness of the lines on the experimental kinogram in Figure 27 as well as on the curve plot on Figure 23. A velocity drop of up to 90% was measured on the experiment.

As illustrated on Figure 27, a qualitative comparison was done on the kinograms of the experimentation and simulation. It is possible to see on it that the motor behaviour differs between the simulation and the experimentation. The two main differences seem to stand in the knee displacement as well as the angular velocity of the thigh relative to the floor. Actually, the simulation tends to keep the knees above toes during all the concentric phase while, during the experimentation, the knees of the lifter kick back and extend quickly at the beginning of the concentric phase and then only the hip extends itself.

Other compared data were the maximal torques at the ankle knee and hip during the concentric phase. The results are listed on Table 14. The main differences between the simulation and the experimentation are that the genetic algorithm tends to overestimate the torque at the ankle but under estimate the torque at the hip.

Max torque	Simulation ankle	Experiment ankle	Simulation knee	Experiment knee	Simulation hip	Experiment hip
Female	425 Nm	332 Nm	687 Nm	691 Nm	402 Nm	510 Nm
Male	1696 Nm	963 Nm	1974 Nm	2047 Nm	1332 Nm	1577 Nm

Table 14 : Maximal torque differences between model and reality

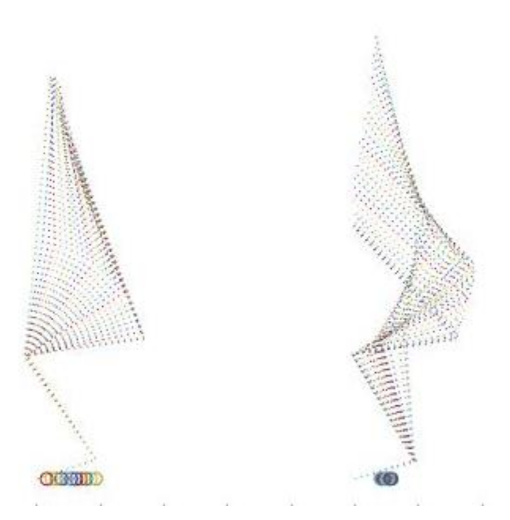
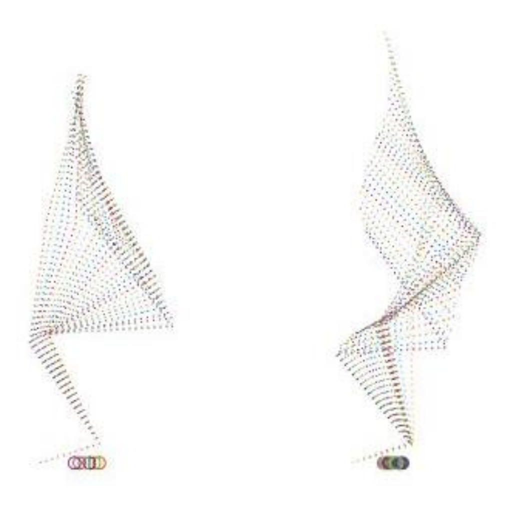
Female lifter	***Male lifter***
	

Figure 27 : Kinogram of the concentric phase of a squat obtained from the simulation (left) and the experiment (right)

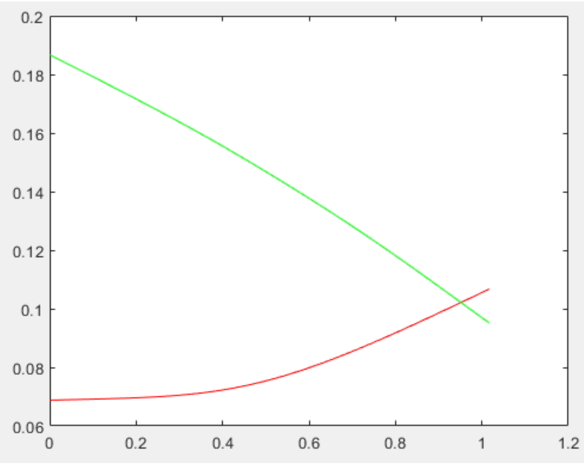
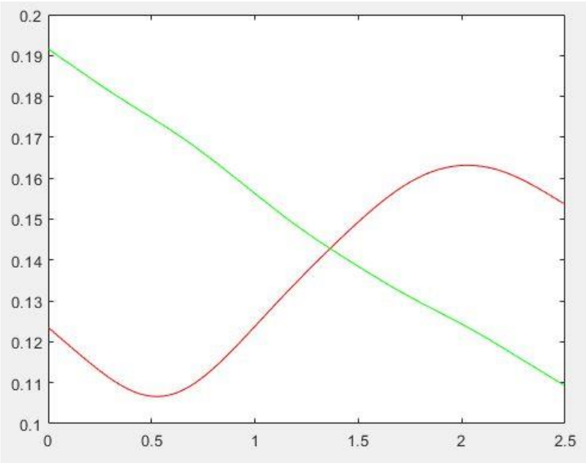
Female lifter	***Male lifter***
	

Figure 28 : Distance between the front of the foot and the CoP depending on time from the model (green) compared to the lifters (red)

5.4 Discussion

As the bar is fixed on the trunk and needs to stay over the base of support, the linear velocity of the bar during the concentric phase and the angular velocity of the thigh relative to the floor are linked together. The velocity of the bar during the concentric phase has already been studied (Larsen et al., 2021b; van den Tillaar et al., 2020) and the shape of the curve has some similarities with Figure 23: The velocity has a first peak and then decreases close to 0 before increasing again at the end of the squat. The part of the curve close to 0 is called the sticking point or sticking region: It is the portion of the lift the most difficult for the lifter and the success of one lift usually depends on whether or not the lifter can get himself out of this part of the lift. In general, this happens a few degrees above thigh being parallel to the floor but, because every lifter has different anthropometrics and muscular strength and weaknesses, the position of the sticking region can vary between individuals (Flanagan et al., 2015).

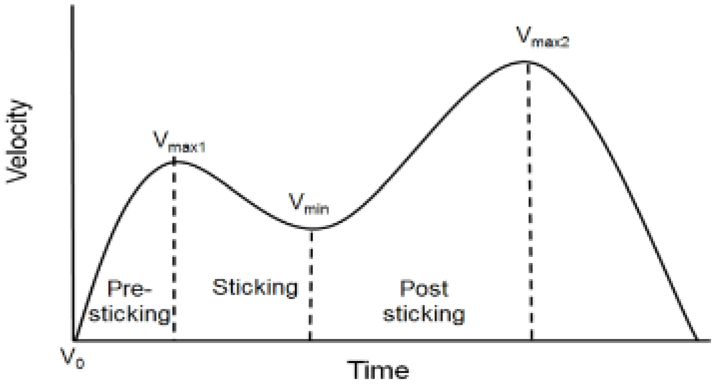
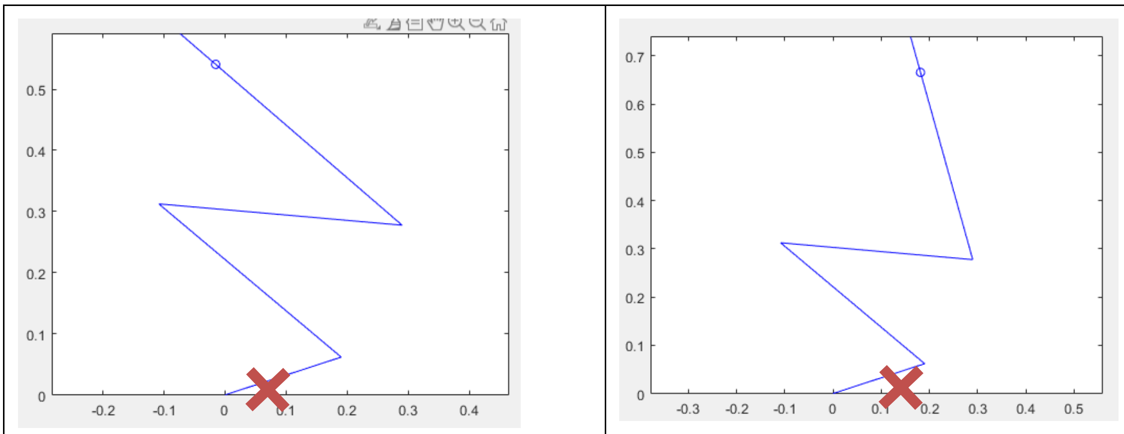


Figure 29 : Typical barbell velocity development during a squat with a sticking region, with different events, e.g., lowest barbell height (V0), first maximal velocity (Vmax1), lowest velocity (Vmin), and second maximal velocity (Vmax2), and different regions.(van den Tillaar et al., 2020)

Regarding the maximal torque at each joint the differences must come from the fact that the torque produced at a joint depends on several factors, such as the angle of the joint, the length and moment arm of the muscles crossing the joint, and the force generated by those muscles. These factors are different for each joint and muscle group, and as a result, the maximum torque that can be produced at one joint is different from the maximum torque that can be produced at another joint. For example, the muscles crossing the ankle joint have a relatively short moment arm compared to those crossing the hip joint. This means that the same force generated by the muscles will result in a smaller torque at the ankle compared to the hip. Similarly, the maximum force that a muscle can generate is also different for each joint and muscle group, further contributing to the differences in maximum torque production. Therefore, it is not accurate to assume that the ankle and hip can produce the same torque as they have different biomechanical characteristics, and a musculoskeletal model should take into account these differences to accurately estimate torque production. As the model is a mechanical one and not a musculoskeletal one it does not have this feature. Hence, as no maximum available torque was set for each joint, the genetic algorithm considers the ankle and hip can produce the same torque, which is false (Anderson et al., 2007).

Regarding the CoP movement, as both elite athletes exhibited the same tendency it was hoped that the genetic algorithm would also adopt the same pattern. Unfortunately, as illustrated on Figure 28, the exact opposite happened.

One of the hypotheses of the model, confirmed by our dynamic simulation on Adams^{TM} is that the squat is slow enough to consider it as a quasi-static movement. Hence, the mechanical energy supplied to the motorization of the joints during the lift mainly comes from the potential energy dissipation. As Figure 30 shows, the CoP position has a great influence on the bar height, hence on its potential energy variation during the concentric phase. From a mechanical point of view, it does seem logic to have the CoP over heels at the beginning of the concentric phase and over toes at the end, which is what the genetic algorithm does.



a) CoP under toes – bar height 0.54m

b) CoP under heel – bar height 0.67m

Figure 30 : Influence of the CoP position on the bar height

To conclude the comparison, Figure 27 shows the differences between the genetic algorithm production and the reality modelization. Both kinograms exhibit a coordinated and realistic extension of the ankle, knee, and hip. This observation is crucial and means that the rules governing the model and the adaptations made on the cost function were effective in creating a realistic movement. It also means that the methodology developed for this project, one of the first projects where the simulation was created without any acquisition but only with anthropometrics, range of motion of the joints, and laws of physics, is effective in modelling a human movement. Some changes could still be made to make the simulation more realistic, but it was chosen to concentrate on the least understandable difference: CoP movements.

5.5 General work tracks

To make the simulation more realistic some changes could be made.

First to respect the “knees locked” rule of powerlifting competition, one condition should be added on the angle of the shank (α_2) at the end of the lift. For now, the only condition is that α_3 the angle of the thigh relative to the floor, should be $\alpha_3 = 90°$ at the end of the squat. It was assumed that this condition would also lead to $\alpha_2 = 90°$ and would model correctly the IPF rulebook that states knees should be « locked » (i.e.: straight legs) at the end of the squat, but a flexion of the knees is still visible on the left kinogram, so the condition $\alpha_2 = 90°$ should be manually added.

The second change to do, that is visible both on Figure 27and Figure 28, is regarding the angular velocity of the thigh. Even though this project is probably the first observing this particular variable other studies in the literature have observed the vertical velocity profile of the bar during heavy squats -Figure 29- (Larsen et al., 2021b; Van den Tillaar, 2019; van den Tillaar et al., 2020) and have observed a first increase of the bar velocity followed by a large decrease until a local minimum called the sticking point is reached, then the velocity increases again in the post sticking region .Because the angular velocity of the thigh was set as a constant this sticking point could not appear on the simulation. This feature could be added to the simulation but, before being implemented, the bar velocity profile should be deeper studied to check if that curve is exactly the same for all the athletes, which means it could be implemented as a parameter on the model, or not. Our guess is that this curve depends on individual factors such as thighs length and muscle force.

Regarding the torques (Table 14) at each joint, the simulation and the modelization of the experiment give results of the same order of magnitude and with less than 25% differences on the extremum. The human body was modelled for this project by a simple torque actuated rigid body model. In reality, the joints are set into motion by the contraction of muscles attached to different bones. The available joint torque depends on many parameters such as the internal moment arm (distance between the insertion of a muscle and the centre of the joint), the size of the muscle and the orientation of the muscle fibres. Even though variability exist depending on the athletes and movements, the gluteus maximus is the strongest muscle of the human body, which means the hip joint is the one that can produce the biggest torque. To better fit the muscle forces and weaknesses of each athlete to improve the simulation without moving to a musculoskeletal modelization the maximal actuator torques available at each joint could be provided by an athlete and a cost function using the ratio $\frac{needed\ torque}{maximum\ torque}$ added in it. That way, the genetic algorithm would decrease its torque demand on the ankle and increase the one on the hips, which would better fit the reality.

Changing the model from a 2D one to a 3D one was also discussed. However, as only adding one degree of freedom at the feet multiplied by more than 10 the time needed to run the genetic algorithm, it is estimated that moving from a 2D to a 3D model would at least double the number of degrees of freedom hence multiply by $10^{nb\_of\_joints}$ the calculus time and make it unacceptable for now. The 3D modelling would need another type of model or calculus methodology to be viable.

5.6 CoP position work tracks

As explained in the previous section, the most striking difference between the simulation and the experimentation was the difference in the Centre of Pressure (CoP) position during the concentric part of the squat. It was observed that the CoP of lifters tends to be under the ball of the foot at the beginning of the concentric phase and moves towards the heel throughout this phase. After discussions with athletes and coaches, they confirmed this trend, pointing out that this shift was induced and not voluntary. This motion is even more interesting since, in powerlifting training, the common cue given to athletes is to use their feet as a tripod and keep their CoP motionless in the middle of this tripod (see Figure 24), which was not the case during the experiments we had accessed to.

The next challenge was to understand why all the lifters have this motion pattern and how to modify the model to obtain such results. Hence, much time was spent after this finding on trying to explain why this difference exists and how to modify the model to better fit the reality.

As the motion can be considered quasi-static no difference will be made between the Centre of Pressure and the Centre of Gravity.

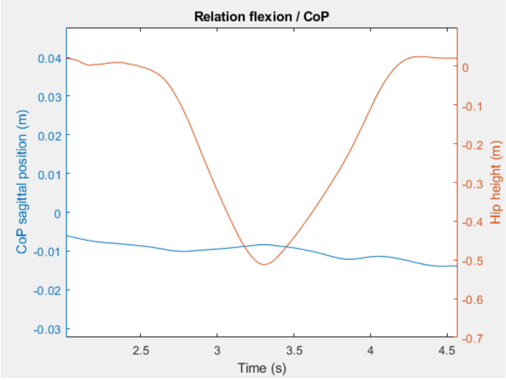
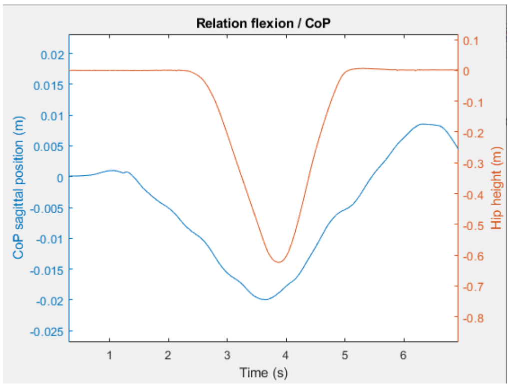
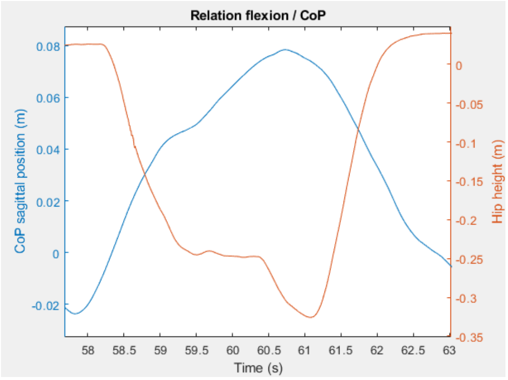
5.6.1 Mobility lack of the Europeans

The first hypothesis was that European inhabitants have less mobility than people from the rest of the world and especially people coming from Asia. This assumption was made because, in weightlifting, where much mobility is needed and athlete often need to squat "ass to grass", the Asian continent dominates the rest of the world: 9 of the 14 gold medals in weightlifting at the Olympic games 2021 were won by Asian countries (7 for China, 1 for Chinese Taipei and 1 for Philippines)(IOC, n.d.). Moreover, the deep squat position is also called the "Asian squat" and used to be a rest position (Figure 31) older Asian used to eat, wait for the bus etc.

Figure 31 : Asian squat position (standje, 2020)

As the laboratory gathers searchers from all around the world, a small preliminary experiment was organized in it to check this hypothesis. The protocol available in French in annexes 7.1 was to equip subjects with reflective markers and make them step on the force plate with the foot stance they preferred; the stance was marked with a pen on a special sheet. Once this was done, the subjects were asked to do one dynamic squat, stop during 1 s, get into the deepest squat position they could reach and hold it for 2 minutes. This duration was arbitrary chosen but enable to separate people being in a comfortable or uncomfortable position in a deep squat. Once the time was over or when the subjects felt too much discomfort, they were asked to stand up again, hold the position 1 s and then do 1 last dynamic squat and hold the position for 1 s. They were asked to hold the erect position because a reflex of many would be to make a step frontward, down the force plate just after the last squat, which would false the results.

The results of this study displayed in Table 15 does not show any relation exists between the continental origin and the mobility nor the CoP position.

<table>
<tr><th>Different patterns</th><th>Number of participants</th><th>Asian participants</th></tr>
<tr><td rowspan="2">
</td><td>6</td><td>1</td></tr>
<tr><td colspan="2">No visible relation between flexion and CoP movement</td></tr>
<tr><td rowspan="2">
</td><td>5</td><td>1</td></tr>
<tr><td colspan="2">The CoP moves toward heels during the eccentric part of the lift and toward toes during the concentric part</td></tr>
<tr><td rowspan="2">
</td><td>2</td><td>0</td></tr>
<tr><td colspan="2">The CoP moves toward toes during the eccentric part of the lift and toward heels during the concentric part</td></tr>
<tr><td colspan="3">Table 15 : Results of the laboratory experiment on the CoP movement of novices</td></tr>
</table>

Differences in the CoP position could also be explained by the fact that the subjects were asked to find a rest position after the first dynamic squat, thus trying not to contract muscles during 2 min, while the exact opposite happens during the powerlifting loaded squat.

Finally, none of the subjects recruited were powerlifters and only two of them said they were used to doing squats or staying in a flexed position. Hence, most of the subjects might have encountered stability issues, explaining why for nearly half of them no relation could be found between the degree of flexion and the CoP position. When they are in the deepest position, the powerlifters want to engage as much muscle mass as possible to produce strength, begin the concentric portion of the squat and get through the sticking point. After this first experiment, the hypothesis of the lack of mobility of the Europeans could not be confirmed.

5.6.2 Better stability under the ball of the foot

The second studied hypothesis was the stability of the lift regarding the position of the CoP. As it is possible to push on your toes if you go too much frontward, this could mean that having a CoP under the ball of the foot is more stable than at the vertical of the heels. To evaluate this, the existing literature on the influence of the CoP position on stability was reviewed (Galarza and Caruntu, 2020; Jeong et al., 2016; Lee and Lee, 2003; Mandalidis and Karagiannakis, 2020; Millard et al., 2012, 2012; Telarolli et al., 2020; Xue et al., 2021). In fact, many of these studies concern manual handlers whose work is to carry loads to store or move them. All these studies agree on the fact that the most stable position is when the CoP is close to the middle of the foot and the stability decreases as much if you move frontward or backward

Other results show that the more flexed the position is, the less stable it is. Moreover, the higher the additional load is carried, the less stable the position is (Lee and Lee, 2003), which makes sense because the higher the load is carried means the higher the centre of mass of the system {subject + load} is and the lowest is the angle needed to move the CoP from the same distance. Finally, the heavier the carried load is, the less the position is stable (Galarza and Caruntu, 2020).

The results of the researches could not confirm the hypothesis that the stability was better under the ball of the foot but do suggest that the stability is best under mid-foot. Nevertheless, these results should be taken with caution as one reason why no conclusive results were found could also be because, to evaluate the stability, the experiments were done in static positions while the squat is a dynamic movement.

5.6.3 CoP needs to go front to go back

The third investigated hypotheses was that the centre of pressure needed to go frontward during the eccentric part of the lift once parallel is reached. This is because, during the beginning of the concentric part of the lift, if the trunk remains parallel to what it was in the deepest position, the extension of the ankle and knee will cause the lifter CoP to go backward. This hypothesis is illustrated on Figure 32.

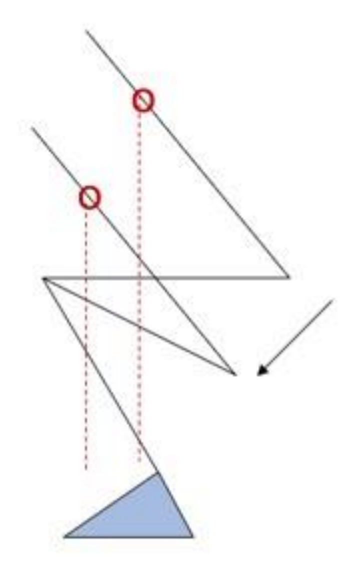


Figure 32 : Third hypothesis illustration

To verify this hypothesis the simulation was modified. Actually, until now the deepest squat position was with the thigh around 5° under parallel, which is still close to parallel. To check the above hypothesis, the model was modified to begin 45° under parallel to see if the CoP position would change. The result of the simulation is that the concentric part of the lift begins with a flexion of the hips and ankle at the same time as the extension of the knees to keep control on the CoP position (Figure 33). Hence the CoP being above heels at the beginning of the concentric portion of the lift is not a problem. Even though the CoP position is not the same on the experimentation, the same pattern is also visible at the beginning of the concentric portion of the lift on some athletes (Figure 34).

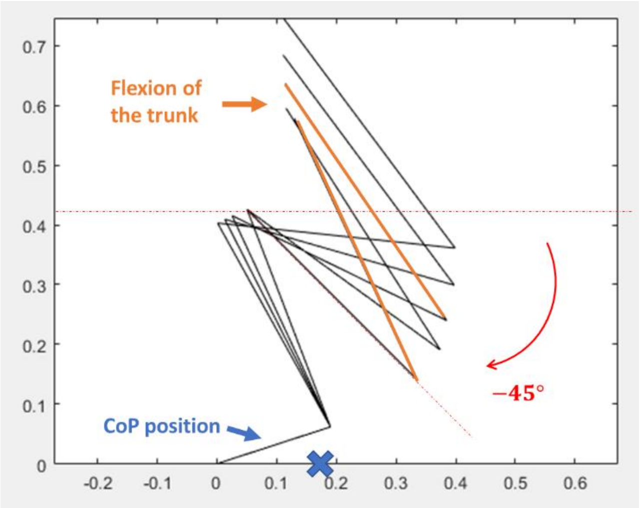


Figure 33 : Kinogram of an optimized squat with a modified starting position

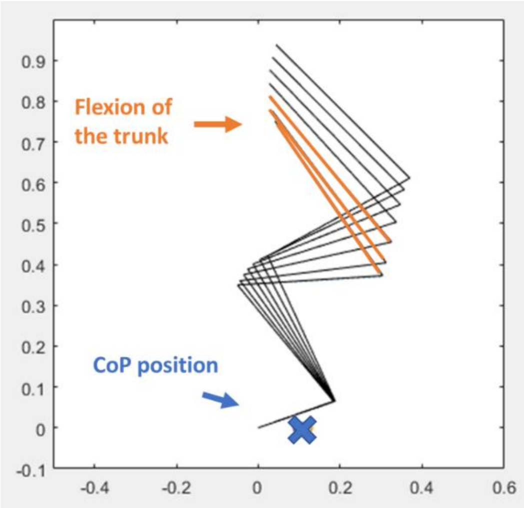


Figure 34 : Kinogram of the modelization of an experiment

Hence the hypothesis was also discarded.

5.6.4 Error caused by the constant velocity hypothesis

As expressed above, the simulation was created for the first time with the angle of the thigh relative to the floor increasing steadily. The experimentations showed that this hypothesis is not correct as, especially under heavy loads, the lifters slow down close to what is called the sticking point.

To make sure this hypothesis did not cause the difference in the CoP movement the simulation was modified to first have the velocity of the thigh relative to the floor evolve the same way as what was found in the experimentations.

The simulation was then run again and even though the energy results differed, the CoP position would not be different;

Hence this hypothesis was also discarded.

5.6.5 Contraction of the triceps surae

The last considered explanation is that, to create an extension torque at the ankle and to use as much muscle mass as possible at the sticking point, the triceps surae needs to contract itself. It seems that, in order to do so, the CoP has to be under the ball of the foot to create a lever arm for the contraction. What was originally just a guess seems to be in agreement with what is done in other sports such as cycle. Actually, even though it is possible to pedal with the heels above the pedal position, it appears that all cyclists position their cleats or feet in order to exert a force with the ball of the foot (Figure 35).

Figure 35: Position of the cleat pads of cyclists under the feet ("-Coombe Millenium Pro Pedals Reviewed," 2021)

Due to the delay after the last experiment and our findings, it was too late to write, validate and run a new experimental protocol to check this hypothesis.

5.6.6 Conclusion

A considerable amount of time has been dedicated to comprehending why the CoP moves in the manner observed in powerlifters, contrary to what the laws of physics predict. Despite not finding a definitive answer, valuable insights have been gained from these studies. Notably, experiments on novice lifters conducted in the laboratory revealed that only a small percentage of them exhibited the same CoP pattern as experienced powerlifters. This outcome suggests that this movement might not be inherent but rather acquired through practice, which could be the focus of further investigation. Significant findings that show an evolution of the CoP movement during the learning of the lift would support the theory that this movement is a performance factor and should not be rectified.

Finally, we strongly encourage researchers interested in this topic to review the literature and research on other sports such as cycling. Cyclists position their cleats under the metatarsal joint instead of the heel, even though they could pedal with the cleats positioned under the heels. If the reason for this is the contraction of the triceps surae, it would be fascinating to transform the model into a musculoskeletal one. Alternatively, more in-depth studies should be initiated to comprehend this unknown influence of the CoP.

Chapter 6 : Conclusion

Weightlifting has been in the Olympic Games since 1896, it consists in two events: the snatch (lifting a barbell overhead in one movement) and the clean and jerk (lifting a barbell overhead in two movements) (Stone et al., 2006). Powerlifting requires maximal strength on 3 lifts, the squat, the bench-press and the deadlift (Ferland and Comtois, 2019). More than Olympic and World games recognised sports, it has been shown that strength training helps athletes of other sports increase their performance (McGuigan et al., 2012). Even though the injury rate of gym training is less than 4 injuries per 1000 hours of training (Parkkari, 2004), it is important for lifters to use a correct technique to limit those risks and improve fitness and performance.

In the literature, it seems widely accepted that different anthropometrical characteristics induce different movement strategies (Cholewa et al., 2019), yet most studies on performance don't take segments lengths into account. This oversight, once transferred to the gyms, induce that the same technical instructions are often given to lifters with different anthropometry and training history. As they are not individualized, these instructions could be at best suboptimal for most athletes, not allowing them to express their full potential and, at worst, dangerous and causing injuries. The most striking example being to keep the knees from moving past the toes (Fry et al., n.d.).

This in-depth research has highlighted the gaps in the literature. All the existing studies but one only observed the kinematics or anthropometrics of athletes without trying to model and simulate the motion to better understand it and bring to light potential factors of performance.

Indeed, the optimization and the associated modelling are complex in this context, this project has focussed first on the simplest lift of both powerlifting and weightlifting: the squat. The squat is used as a competitive lift in powerlifting but is also part of the snatch and clean in weightlifting. Moreover, during a powerlifting squat the bar is motionless on the back of the athlete and the motion is symmetrical. Hence it can be modelled in 2D in the sagittal plane only with 3 bodies to model the lifter: the shank, the thigh and the trunk. As the ankle mobility can be a limiting factor during a squat and can be modified artificially it was decided to add a 4th body: the foot. Also, even though its position is fixed compared to the ground during all the lift it seemed important to include it to be able to visualize the centre of pression (CoP) position compared to the base of support (the area of the foot on the ground).

To make sure to control all the parameters, the mechanical model used for the simulation was specifically developed and every parameter could be changed if needed to adapt to a specific subject. Nevertheless, the methodology and the developed tools can be generalized to more complex cases, which is a perspective to this study. To optimize the motion of a lifter the major issue was to consider his anthropometrics and especially segment lengths, bodyweight, and mobility (range of motion at the joint). Other important added parameters were the weight and the position of the bar compared to the 7th cervical vertebra to be able to also control this parameter as position of the bar on the back, “high bar or low bar” often induce different motor strategies.

Once the mechanical model was set, an optimization algorithm had to be developed. Once again, we chose to develop our own genetic algorithm to control all the parameters and minimize the intrusiveness in the model part of the code. This core part of the PhD enables to run the simulation without depending on any software or black box. The fact that the algorithm converges, independently from its starting point, to a solution with the lowest cost function enables us to conclude that it was successful. On the other hand, some experiments were run and another algorithm was developed such that an avatar was created based on the data of the experimentation and an optimized motion was searched thanks to the genetic algorithm especially for this avatar which had the same anthropometrics as the lifter during the experiment.

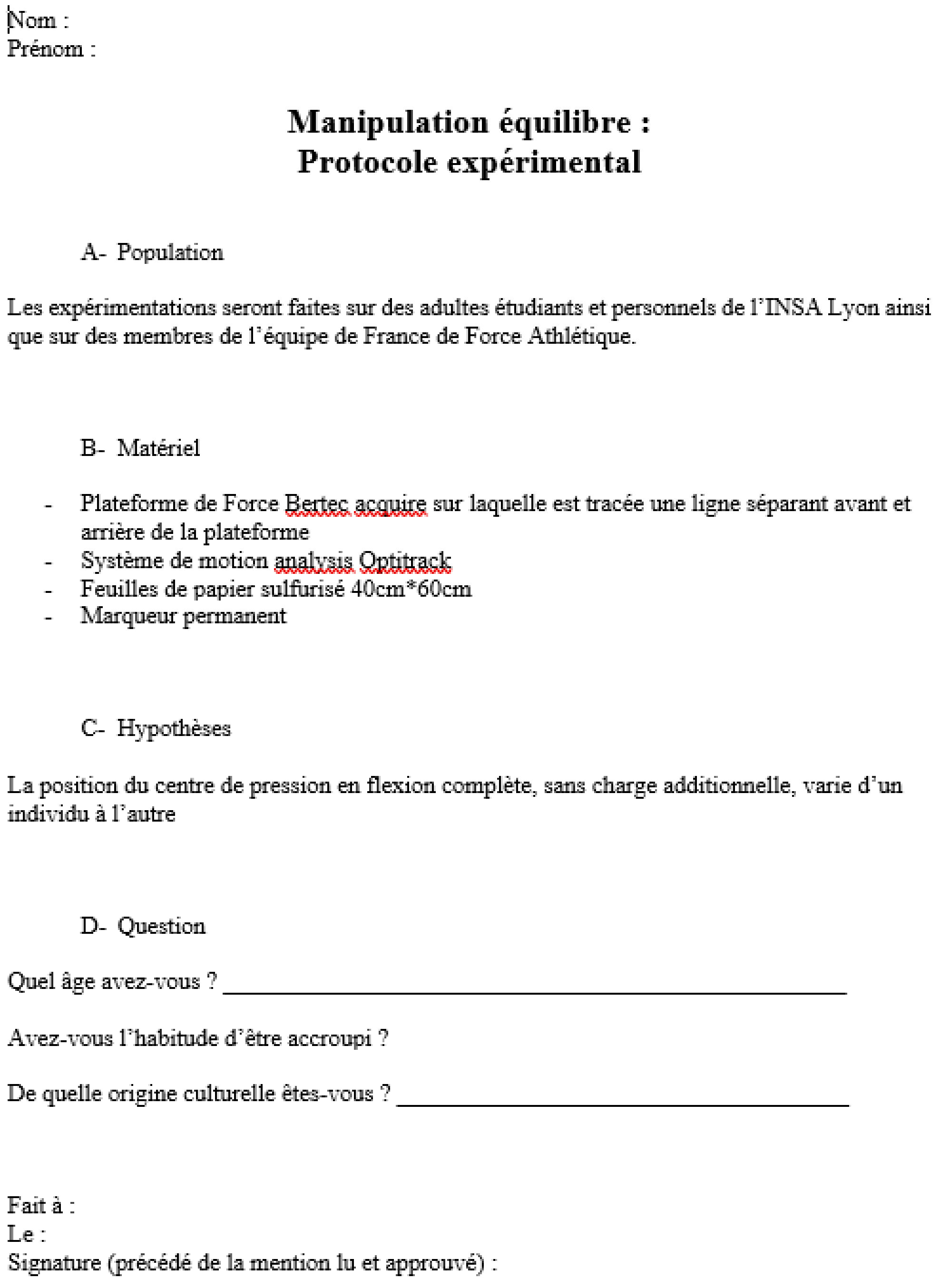
This comparison between the modelization of the experimentation and the simulation was one of a kind. It enabled us to validate some hypotheses of the model and disprove other ones such that the CoP position during the lift even though a way to modify the model to stick to the reality regarding the CoP position is still under development. The process we have developed and followed could be applied to many other areas like manual handling or sport such as golf or archery. Creating a personalized avatar of each athlete and being able to “experiment” with a predictive model on it could interesting in the high-performance research field. Indeed, elite athletes are difficult to study. On one hand they would like and need to benefit from science because every small improvement can make a huge difference in tight battles at the international level. On the other hand, high level training means scrupulously respecting a precise training program. In powerlifting for example, training for one competition is divided in macro-, meso- and micro- cycles which organize the athlete program from the yearly calendar to monthly blocks and weekly training days. In addition, a huge part of the performance comes from nervous and muscular recovery as well as hydration around the trainings, which means elite athletes often refuse to volunteer to scientific researches because forcing themselves into a protocol could increase their fatigue and prevent them from performing well in training hence decrease their progression and increase their risk of injury. Therefore, being able to capture athletes' anthropometrics and motion in training conditions and using the data to create a personalized avatar could help scientist a lot. Once the avatar is created they could experiment on it and simulate as many protocols as they want without inducing any fatigue on the athletes.

This work also presents some limitations. First the model was only 2D with 4 bodies and creating a 3D model with more bodies could make the calculation time grow exponentially, especially as we discretized all the reachable positions of the avatar. Then we created a quasi-static model which fits the reality for the powerlifting squat example but could not be used for other weightlifting movements such as the snatch or jerk for which the velocity is a performance factor. Also, the position of the markers is not the most precise way to calculate the positions of the joint centers, the bone geometries and the axes of the joints of the limbs. To do that, a biplanar radio such that EOS could be used to give precise data. In addition, the model was mechanical only and no muscle behavior were added. This lack could be the reason why differences were found between the simulation and the modelization of the experiment regarding the maximal torque produced by each joint as well as the CoP movement. One way to calculate physiological muscle parameters such that the maximum isometric force, the tendon slack length, or the optimal muscle fibre length could be to use ultrasound acquisitions (Akay et al., 2017). The customizing muscle paths based on stereo-radiographic imaging method developed by Thibault Marsan in his PhD (Marsan, 2021) could also help create a personalized musculoskeletal avatar.

These are all future prospects for the work on movement optimization for elite sport.

Chapter 7 Annexes

7.1 Protocol given to subjects for the CoP experiment



Nom :
Prénom :

Manipulation équilibre :
Protocole expérimental

A- Population

Les expérimentations seront faites sur des adultes étudiants et personnels de l'INSA Lyon ainsi que sur des membres de l'équipe de France de Force Athlétique.

B- Matériel

- Plateforme de Force Bertec acquire sur laquelle est tracée une ligne séparant avant et arrière de la plateforme
- Système de motion analysis Optitrack
- Feuilles de papier sulfurisé 40cm*60cm
- Marqueur permanent

C- Hypothèses

La position du centre de pression en flexion complète, sans charge additionnelle, varie d'un individu à l'autre

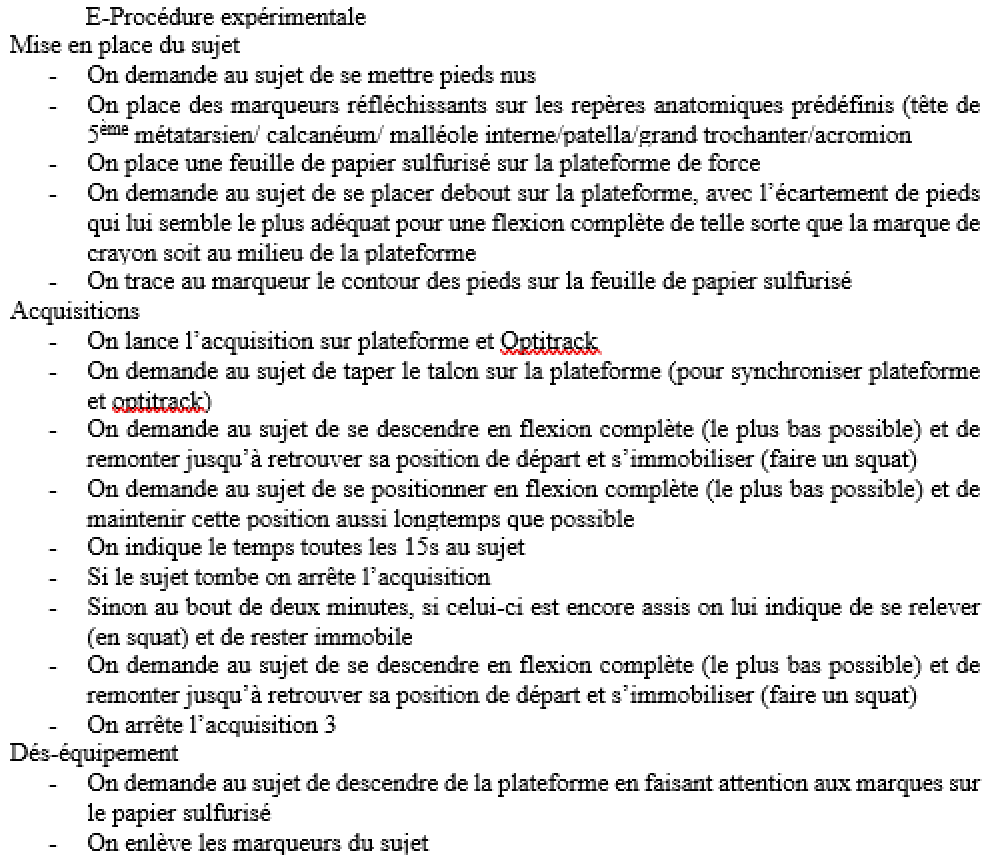
D- Question

Quel âge avez-vous ? ____

Avez-vous l'habitude d'être accroupi ?

De quelle origine culturelle êtes-vous ? _________________________________

Fait à :
Le :
Signature (précédé de la mention lu et approuvé) :



E-Procédure expérimentale

Mise en place du sujet

- On demande au sujet de se mettre pieds nus
- On place des marqueurs réfléchissants sur les repères anatomiques prédéfinis (tête de 5ème métatarsien/ calcanéum/ malléole interne/patella/grand trochanter/acromion
- On place une feuille de papier sulfurisé sur la plateforme de force
- On demande au sujet de se placer debout sur la plateforme, avec l'écartement de pieds qui lui semble le plus adéquat pour une flexion complète de telle sorte que la marque de crayon soit au milieu de la plateforme
- On trace au marqueur le contour des pieds sur la feuille de papier sulfurisé

Acquisitions

- On lance l'acquisition sur plateforme et Optitrack
- On demande au sujet de taper le talon sur la plateforme (pour synchroniser plateforme et optitrack)
- On demande au sujet de se descendre en flexion complète (le plus bas possible) et de remonter jusqu'à retrouver sa position de départ et s'immobiliser (faire un squat)
- On demande au sujet de se positionner en flexion complète (le plus bas possible) et de maintenir cette position aussi longtemps que possible
- On indique le temps toutes les 15s au sujet
- Si le sujet tombe on arrête l'acquisition
- Sinon au bout de deux minutes, si celui-ci est encore assis on lui indique de se relever (en squat) et de rester immobile
- On demande au sujet de se descendre en flexion complète (le plus bas possible) et de remonter jusqu'à retrouver sa position de départ et s'immobiliser (faire un squat)
- On arrête l'acquisition 3

Dés-équipement

- On demande au sujet de descendre de la plateforme en faisant attention aux marques sur le papier sulfurisé
- On enlève les marqueurs du sujet

7.2 CERSTAPS protocol

Comité d'Ethique pour la Recherche en Sciences et Techniques des Activités Physiques et Sportives

Formulaire de soumission au Comité d'Ethique pour la Recherche en Sciences et Techniques des Activités Physiques et Sportives (CERSTAPS)

Titre du projet :

Modélisation biomécanique du squat : identifier les facteurs de performance

RESUME du projet ***(250 MOTS MAX)***
Le coaching sportif repose sur un mélange de ouï-dire et de traditions. Les pratiques des meilleurs athlètes ayant été copiées et transmises par les entraîneurs au fil des générations et ce, bien que les explications de leurs effets soient souvent absentes ou manquent d'assise scientifique. Ces approches quelque peu dogmatiques de l'entraînement ont l'effet secondaire malheureux de préserver les croyances dans la conviction qu'elles sont optimales, alors que des techniques différentes et meilleures peuvent exister selon la morphologie et les capacités musculaires de chaque athlète. De plus, bien que ces pratiques puissent être efficaces, elles se trouvent régulièrement inadaptées à certains athlètes et peuvent entrainer une stagnation en deçà des capacités réelles de l'athlète, voir même des blessures pouvant mettre un terme à la carrière de haut niveau de certains.

L'objectif central de notre projet est le développement d'un modèle humain virtuel personnalisé permettant l'analyse dynamique du corps en mouvement en le reliant aux mécanismes mis en jeu par l'athlète au cours de sa pratique. A partir d'une intégration des connaissances scientifiques et méthodologiques dans le domaine de l'expertise de la performance sportive, les concepts scientifiques propres à l'analyse biomécanique du mouvement sont établis en intégrant les contraintes isométriques rencontrées. Une meilleure compréhension du mouvement et une réduction du risque de blessure sont recherchées.

Avertissement relatif à la loi informatique et libertés
Les recherches sur la personne humaine consistent généralement dans le traitement de données personnelles qui nécessitent une déclaration à la CNIL et parfois une demande d'autorisation. Le CERSTAPS n'a pas vocation à traiter ce sujet mais peut vous alerter sur la nécessité d'une telle démarche. Pour connaître les obligations liées à votre recherche du point de vue de la loi informatique et libertés et engager les formalités de déclaration préalable, nous vous invitons à prendre contact, dans un premier temps, avec le correspondant Informatique et Libertés (CIL) de votre Université :

Domaine scientifique : Biomécanique

Chercheur(s) titulaire(s) responsable(s) scientifique(s) du projet :

Benyebka Bou-Saïd

Professeur des Universités

Lieu(x) de recherche (endroit(s)) où l'étude va être conduite :

INSA Lyon

Centres d'entraînements des athlètes équipe de France

CREPS Vichy

Je prends connaissance du fait que l'avis rendu par le CERSTAPS ne concerne que le projet de recherche présenté dans ce document.

Date : 30/07/2021

Signature du responsable scientifique :

1. Description[VN1] sommaire du projet

Contexte et intérêt scientifiques

Plus que des sports, l'haltérophilie et la force athlétique sont aujourd'hui très utilisés dans le monde de la préparation physique et de la performance. Comme les deux activités consistent à soulever des charges additionnelles, elles se doivent d'être bien exécutées afin de réduire le risque de blessures et d'augmenter la performance.

A ce jour, les conseils de coaches expérimentés, diplômés ou auto-proclamés sont très répandus dans les salles de sport et sur la toile et ce, bien que la littérature scientifique dans le domaine reste très pauvre comme le soulignent Lester K. W. Ho et al. ainsi que Pierre-Marc Ferland et Alain S. Comtois dans leurs revues respectives « Reviewing Current Knowledge in Snatch Performance and Technique: The Need for Future Directions in Applied Research » et « Classic Powerlifting Performance: A Systematic Review ». De plus, les mêmes consignes techniques sont régulièrement données a des athlètes de morphologie, sexe, capacité et passé sportifs différents. Plus qu'un frein à la performance, un coaching inapproprié peut aussi augmenter le risque de blessure, il semble donc pertinent de s'intéresser de plus près aux mécanismes mis en jeu par l'athlète lors de sa pratique.

Une optimisation des performances avec évaluation des risques lésionnelles aux limites de la performance est recherchée. La principale originalité de notre projet est que nous nous basons sur des techniques de contrôle optimal sur fonction multi-variables avec une application précise au geste sportif qui nous a permis de développer un modèle bio-fidèle virtuel. Cette démarche pourra être généralisée à d'autres sports à partir d'un modèle générique.

Peu de travaux publiés existent sur cet aspect précis. Nous pouvons citer néanmoins les travaux de Sh. Lenjannejadian et M. Rostami sur le tirage d'haltérophilie dans l'article « Optimal Trajectories of Snatch Weightlifting for Two Different Weight Classes by using Genetic Algorithm », bien que cet article s'intéresse aux catégories de poids plus qu'aux longueurs de segments.

Le projet est déjà très avancé et un modèle mécanique a dors et déjà était développé. Cependant, certains mécanismes liés à l'humain restent à identifier afin de compléter ce modèle.

1.1 Objectifs

L'objectif central de ce projet est le développement d'un modèle virtuel bio-fidèle personnalisé permettant une paramétrisation du mouvement dynamique du corps au cours d'une flexion extension des membres inférieurs, paramétrisation donnant accès à des choix d'optimisation du geste sportif sans risque lésionnel

1.2 Hypothèses générales

Suite à des observations visuelles faites sur le terrain lors des championnats du monde de force athlétique, il apparait que, bien qu'ils aient des morphologies et des mouvements bien différents, la plupart des athlètes internationaux ont des variations de leur zone d'appui plantaire durant le mouvement du squat. Cette observation est d'autant plus étonnante que le déplacement de ce point d'appui se fait à l'inverse de ce que le modèle mécanique développé trouve comme optimal.

L'hypothèse principale est donc que le centre de pression du système athlète + barre est mobile au cours du temps et se situe à l'avant du pied au début de la phase concentrique du squat.

La seconde hypothèse étant que la stratégie motrice de chaque athlète dépend de ses longueurs de segments.

Une expérimentation est donc nécessaire tout d'abord pour confirmer cette observation puis pour identifier les causes et les effets attenants à chaque schéma moteur.

1.3 Conflits d'intérêts

Pas de conflit d'intérêt

2. Matériel et Méthodes

2.1 Participants

Nombre exact de participants ou « fourchette » approximative et critères utilisés pour fixer ce nombre :

L'objectif étant de constituer une base de données exploratoire, nous espérons obtenir les données de 80% de l'effectif listé haut niveau de l'équipe de France, soit 20 athlètes[VN2]..

Recrutement :

Mode de recrutement : *Par listings sur la liste des athlètes en Force Athlétique de niveau international*

Lieu de recrutement : *Le recrutement aura lieu par email grâce au listing des athlètes de niveau international*

Critères[VN3] de sélection [VN4]: *Athlète de niveau international en Force Athlétique dans sa catégorie d'âge[VN5] et de poids*

Critères de non inclusion : Blessure[VN6] entrainant une incapacité de la pratique du squat

Indemnisation éventuelle des sujets : Pas d'indemnisation des sujets

2.2 Méthode

Description du protocole :

Procédure expérimentale

Le sujet est accueilli en salle d'expérimentation. Il est informé de la nécessité de faire un squat type compétition à une charge supérieure ou égale à 75% de son 1RM. Le nombre de répétitions est laissé à l'appréciation de l'athlète pendant la série. Il lui est demandé de continuer sa série jusqu'à fournir un effort d'intensité modéré à élevé.
Le temps nécessaire à l'échauffement cardiovasculaire et articulaire sera laissé à l'appréciation de l'athlète selon la charge de travail qu'il aura déterminé.
Afin de suivre le mouvement des articulations, des marqueurs réfléchissants seront ensuite collés sur les repères anatomiques en accord avec le protocole de Rizzoli détaillé dans l'article « Multi-Segment Trunk Kinematics during Locomotion and Elementary Exercises » de Alberto Leardini et al.
Une fois cette étape terminée, l'échauffement spécifique ou montée en charge pourra prendre place selon les habitudes de l'athlète et la charge de travail qu'il aura déterminé.

L'athlète effectue son échauffement et sa montée en charge comme à son habitude en respectant un temps de repos de 3 à 10min entre les différentes barres d'échauffement jusqu'à arriver à la charge de travail.

Etapes de l'acquisition :
- *La barre est placée sur les supports et chargée à 75% ou + du maximum théorique du jour sur une répétition (1RM) (les athlètes étant tous expérimentés, ils sont capables lors de la chauffe d'évaluer leur 1RM du jour)*
- *L'athlète se place sous la barre prêt à*
- *L'athlète saisit la barre sur les supports et recule jusque sur la plateforme de force*
- *Une fois sa position jugée adéquate et immobile pour le départ, les acquisitions sont lancées.*
- *Lorsqu'il se sent prêt, l'athlète débute sa série et effectue 3 répétitions à une charge de 75% ou + de son 1RM*
- *Une fois la position finale (droit genoux verrouillés) immobile atteinte les acquisitions sont arrêtées et l'athlète repose la barre sur les supports.*

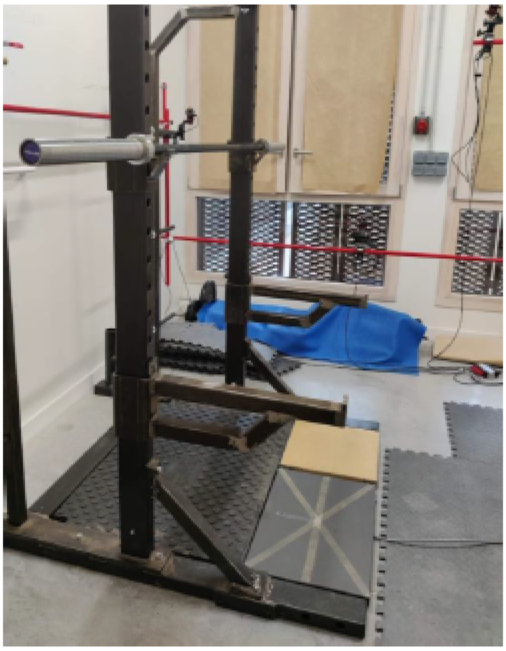
Questionnaire (donné après la fin des acquisitions) :
- *Citez 3 points techniques sur lesquels vous êtes attentif durant le mouvement.*
- *Sur quelle partie du pied êtes-vous le plus en appui en bas du squat ?*
- *Selon-vous, quel groupe musculaire sollicitez-vous le plus dans la phase concentrique du squat ?*
- *Selon-vous, où se situe votre « point dur » ?*
- *Selon-vous, sur un effort maximal, quels sont chez vous les points critiques (techniques et/ou musculaires) qui peuvent engendrer un échec ?*

Matériel utilisé :

Matériel spécifique à la réalisation d'un squat

- *Un rack à squat ou cage à squat ou supports de type chandelle*
- *Une barre de force homologuée qui pourra aussi être instrumentée*
- *Un ensemble de poids homologués pesant de 1,25kg à 25kg*
- *Des systèmes de serrages homologués de 2,5kg chacun*

Le matériel scientifique utilisé sera constitué d'une plateforme de Force, nécessaire pour mesurer les variations de position du centre de pression du système {athlète barre} lors du mouvement. Le sol sera mis à niveau avec la plateforme à l'aide de dalles, visibles en noir et bois sur la photo ci-contre. Des marqueurs réfléchissants seront placés sur les repères anatomiques pré-identifiés. La position de ces derniers au cours du mouvement sera capturée par un système de motion analysis de type Optitrack.



Calendrier des évaluations ou observations : *Une unique session d'évaluation sera programmée par participant, celle-ci aura lieu sur le campus de l'INSA Lyon ou sur le lieu d'entraînement des participants. Si besoin, les frais de déplacement seront pris en charge par l'INSA Lyon. La durée des acquisitions sera d'environ une heure et sera effectuée en accord avec les mesures sanitaires en vigueur.*

Durée de l'étude : *Les données seront recueillies durant la saison sportive 2021-2022 soit entre le 1er janvier 2022 et le 31 décembre 2022*

Analyse des données : *Les données recueillis seront ajoutées au modèle biomécanique développé afin de mesurer notamment le déplacement de la barre dans le plan sagittal, les couples aux articulations selon les phases du mouvement et les groupes musculaires les plus sollicités selon la trajectoire utilisée.*

2.3 Bénéfices et risques prévisibles et connus pour la santé physique et mentale (estime de soi, etc.) et la vie sociale (réputation)

Présentez les bénéfices de votre étude.

Le bénéfice majeur sera la progression des connaissances scientifiques sur le mouvement du squat, de son optimisation et de la minimisation des risques lésionnels.

Pas de bénéfice immédiat pour les participants, l'objectif étant avant tout la création d'une base de données exploratoire.

Répondre par **oui ou non** dans la case correspondante :

Non	Duperie lors de l'expérimentation ? *Si oui, ce dossier doit présenter une description de la duperie utilisée et une explication de la façon de la dévoiler aux sujets à la fin de l'étude et de leur préciser les véritables objectifs de l'étude. En outre, on doit amener des arguments montrant que la dissimulation de certains aspects du protocole est indispensable au regard des objectifs et des enjeux, et qu'aucun des aspects dissimulés aux sujets n'est susceptible de menacer leur sécurité ou leur dignité.*
Non	Questions considérées par le participant comme personnelles ou confidentielles ?
Non	Matériaux considérés par le participant comme menaçants, choquants, répugnants ?
Non	Possible atteinte à la vie privée du participant, de sa famille, incluant l'utilisation d'informations personnelles ?

Non	Utilisation de stimuli physiques (auditifs, visuels, haptiques, etc.) autre que des stimuli associés à des activités normales ?
Non	Privation de besoins physiologiques (boire, manger, dormir, etc.)
Non	Manipulation de paramètres psychologiques ou sociaux comme la privation sensorielle, l'isolement social ou le stress psychologique ?
Oui	Efforts physiques au delà du niveau considéré comme modéré pour le participant ?
Non	Exposition à des drogues, produits chimiques ou agents potentiellement toxiques ?

L'effort physique demandé est au-delà du niveau considéré comme modéré par le participant mais, ce dernier étant un athlète entrainé, c'est un effort qu'il a l'habitude de fournir et ne présentant pas de danger pour son intégrité physique.

2.4 Vigilance/ Arrêt prématuré de l'étude

Critères d'arrêt de l'étude pour un sujet qui y participe

Retrait du consentement, blessure entre la signature du protocole et le début des acquisitions ainsi qu'incapacité à fournir un pass sanitaire valide. Les sujets et les expérimentateurs seront aussi tenus de respecter les mesures sanitaires en vigueur.

3. Traitement des données - respect de la vie privée du participant

Le porteur de projet doit préciser les conditions dans lesquelles les informations récoltées seront traitées, anonymisées, conservées, ainsi que les mesures garantissant le respect de la vie privée dans la mise en œuvre du protocole et dans la diffusion des résultats de l'étude.

3.1 Confidentialité

Procédé d'anonymisation

La confidentialité sera garantie par un tableau de correspondance qui permettra à chaque sujet ou collectif d'être désigné par un identifiant prenant la forme d'un numéro aléatoire dans les analyses et documents numériques ou papier.

Personnes ayant accès aux données

Seuls les participants et les responsables scientifiques du projet auront accès aux données. Les participants n'auront accès qu'à leurs données personnelles. Seuls les responsables scientifiques auront accès au tableau de correspondance.

3.2 Archivage

Type de données archivées (préciser si les données sont identifiantes, directement ou par recoupement) : Données biomécaniques identifiantes par recoupement

Durée de l'archivage : 15ans

Lieu de l'archivage : LaMCoS, INSA Lyon

Personne responsable : Emmanuel Montero

Possibilité de destruction à la demande du participant : Oui

4. Notice d'information et consentement éclairé

Le dossier communiqué au CERSTAPS doit comprendre la notice d'information destinée aux sujets, le formulaire de consentement et les affiches éventuelles de publicité. Ces documents sont rédigés dans une langue comprise par le sujet (française par défaut ou préciser une autre langue si nécessaire, le cas échéant, voir avec le CERSTAPS s'il y a lieu de fournir une traduction). L'information donnée doit être claire, intelligible et concise.

Les modalités de recueil de consentement doivent être précisées. Le droit au refus, de retrait et de suivi de la recherche doit être indiqué dans le protocole mais aussi dans la fiche de consentement.

4.1. Précisions sur la notice d'information

Tout participant présélectionné sera préalablement informé par le responsable scientifique des objectifs de l'étude, de sa méthodologie, de sa durée, de ses contraintes et des risques prévisibles. Il sera notamment précisé au participant qu'il est entièrement libre de refuser de participer à l'étude et de retirer son consentement à tout moment sans encourir aucune responsabilité ni aucun préjudice de ce fait. Il lui sera également fait mention de la possibilité de demander la destruction des données le concernant.

Un document résumant les renseignements donnés par le responsable scientifique lui sera remis (Notice d'information - Annexe n°1).

Pensez à adapter votre notice d'information à votre protocole de recherche et au public visé (par exemple, adaptation de l'information si la notice est à destination d'un enfant).

4.2 Consentement éclairé

S'agissant des recherches non interventionnelles, après s'être assuré de la bonne compréhension des informations fournies, le Responsable scientifique sollicitera du participant son consentement pour participer à l'étude. S'il accepte, le participant signera le formulaire de consentement préalablement à la réalisation de l'étude (Formulaire de consentement éclairé - Annexe n°2).

Comité d'Ethique pour la Recherche en Sciences et Techniques des Activités Physiques et Sportives

ANNEXE 1 - notice d'information[VN7]

La notice d'information est à remettre aux personnes sollicitées pour participer à une recherche.

Titre du projet :

Modélisation biomécanique du squat : identifier les facteurs de performance

Chercheur(s) titulaire(s) responsable(s) scientifique(s) du projet : Bou-Saïd Benyebka

Lieu de recherche : LaMCoS INSA de Lyon

But du projet de recherche :

L'objectif de ce projet est la création d'une base de données exploratoire concernant le mouvement du squat ou flexion de jambe. L'objectif de cette base de données est d'aider les chercheurs à caractériser le mouvement en fonction de paramètres morpho-anatomiques tels que la longueur des segments de l'athlète.

Si vous acceptez de prendre part à cette étude, vous participerez à une expérience pendant laquelle vous effectuerez un triplé sur le mouvement du squat dit « type compétition » à une charge de 75% de votre 1RM du jour. Nous enregistrerons à l'aide d'une plateforme de force et de marqueurs réfléchissant vos appuis au sol ainsi que les mouvements de votre corps et de la barre. A la fin de l'expérience, vous remplirez un questionnaire sur votre profil sportif (environ 50 minutes d'acquisitions + 5 minutes de questionnaire).

Vos droits à la confidentialité

1/ les données obtenues seront traitées avec la plus entière confidentialité ;

2/ on voilera votre identité à l'aide d'un numéro aléatoire ;

3/ aucun autre renseignement ne sera dévoilé qui puisse révéler votre identité ;

4/ toutes les données seront gardées dans un endroit sécurisé et seuls le(s) Responsable(s) scientifique(s) et les chercheurs adjoints y auront accès.

Vos droits de vous retirer de la recherche en tout temps

Préciser les points suivants au participant :

1/ Votre contribution à cette recherche est volontaire

2/ Vous pourrez vous retirer ou cesser votre participation à tout moment et demander que vos données soient détruites sans conséquence

3/ Votre décision de participer, de refuser de participer, ou de cesser votre participation n'aura aucun effet sur vos notes, votre statut, vos relations futures avec le laboratoire LaMCoS, l'INSA Lyon ou la FFForce.

Bénéfices

Les avantages attendus de cette recherche sont d'obtenir une meilleure compréhension du geste sportif du squat et des facteurs qui influencent le schéma moteur d'un athlète. Une meilleure compréhension de ces facteurs pourra contribuer à améliorer les conseils techniques donnés par les entraineurs lors de la formation des futurs athlètes.

Risques possibles

Comité d'Ethique pour la Recherche en Sciences et Techniques des Activités Physiques et Sportives

À notre connaissance, cette recherche n'implique aucun risque ou inconfort autre que ceux liés à votre pratique sportive.

Diffusion

Cette recherche sera diffusée dans des colloques et elle sera publiée dans des actes de colloque et des articles de revue académique.

Vos droits de poser des questions en tout temps

Vous pouvez poser des questions au sujet de la recherche en tout temps en communiquant avec le Responsable scientifique du projet par courrier électronique à benyebka.bou-said@insa-lyon.fr (ou par téléphone au 0635273635).

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FOLIO ADMINISTRATIF

THESE DE L'INSA LYON, MEMBRE DE L'UNIVERSITE DE LYON

NOM : PEYRAUD - Nom de Jeune Fille : VEDEL

DATE de SOUTENANCE :

Prénom : Charlotte

TITRE : Increasing lifting performances: Biomechanics for an optimized training

NATURE : Doctorat

Numéro d'ordre NNT :

Ecole doctorale : Mécanique, Energétique, Génie Civil et Acoustique (MEGA)

Spécialité : Biomécanique

RESUME : More than sports, weightlifting and powerlifting are widely used in fitness/resistance training for sport performance. As they both consist of lifting additional weights they must be well executed to avoid injuries and enhance fitness and performance. To date, pieces of advice from experienced or graduated or self - proclaimed coaches, swarm in gyms and on the web, but very little are based on scientific knowledge. The same technical instructions are often given to men and women with different anthropometry and training history. As they are not individualized, these instructions could be at best suboptimal for most athletes, not enabling them to express their full potential and, at worst, dangerous and causing injuries. The central objective of our project is the development and validation of an optimised personalized virtual human model. On the one hand, a virtual mechanical model of an athlete squatting was numerically designed and set into motion by the development of a genetic algorithm minimizing a cost function. On the other hand, an experiment was designed to measure the squat kinematics of experienced athletes. The results of the simulation and experimentation were then confronted, the differences explained and areas of improvement listed.

MOTS CLES : optimization – squat – lifting – genetic algorithm - biomechanic – simulation

Laboratoire de recherche : Laboratoire de Mécanique des Contacts et des Structures (LaMCoS)

Directeur de thèse : Benyebka BOU-SAÏD

Président du jury :

Composition du jury :