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Quantitative Analysis of Kinematic Asymmetry in Push-Ups and Its Correlation with Muscular Fatigue

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Abstract: ***This study investigates the relationship between kinematic asymmetry and muscular fatigue during push-ups. Kinematic asymmetry refers to the differences in joint movements (e.g., elbows and wrists) between the left and right sides of the body. This research aims to analyse these asymmetries and explore their relationship to fatigue development. A custom push-up pose estimation tool, built in Python using OpenCV and Mediapipe, was developed to track and measure joint angles in real-time while participants performed push-ups. Data was then collected across multiple repetitions until fatigue prevented the participants from maintaining proper form. The results showed a significant increase in both elbow and wrist asymmetry as participants progressed through repetitions, indicating that fatigue impairs the ability to maintain symmetrical movement patterns. A strong positive correlation ($R^2 = 0.85$) was observed between elbow asymmetry and repetition count, while a moderate correlation ($R^2 = 0.65$) was found for wrist asymmetry. These findings suggest that kinematic asymmetry can serve as an early indicator of fatigue, providing valuable insights for trainers and athletes to detect performance decline and adjust training programs accordingly. The study highlights the importance of monitoring joint angles during push-ups to prevent uneven muscle development and reduce the risk of injury. Applying real-time feedback systems, such as the custom pose estimation tool developed in this research, athletes and participants can possibly improve their form and optimize training outcomes. This research contributes to the growing body of knowledge on kinematic asymmetry and its implications for athletic performance, injury prevention, and rehabilitation.***

Keywords: kinematic asymmetry, muscular fatigue, push-up performance, injury prevention, pose estimation, biomechanics, fatigue assessment, rehabilitation, training optimization, elbow and wrist asymmetry, performance monitoring, computer vision in sports, fatigue threshold, strength training

1. Introduction

1.1 Background and Motivation

Push-ups are a commonly performed exercise to increase upper body strength and endurance. However, as muscular fatigue sets in, inconsistency in form, especially between the left and right sides, can develop. These inconsistencies, also known as **kinematic asymmetries**, are frequently disregarded but may offer valuable insights into fatigue progression and injury risk.

For athletes, trainers, and researchers, understanding how fatigue impacts movement symmetry could help design more accurate training programs and prevent particular injuries. While existing studies investigate fatigue and general form breakdown, little significant research has been done specifically on **kinematic asymmetry and fatigue development** during push-ups.

Additionally, the classification analysis could serve as a basis for the rehabilitation process, as by determining these asymmetries, the direction for improving the symmetry and functional capacities can be set. It is one area that is particularly interesting in sports medicine since overuse injuries must always be avoided. The present study is an effort to obtain additional knowledge on **kinematic asymmetry**, its relation to muscular fatigue, and how a better understanding of these components could contribute to optimization of athletic performance and reduce risks of injury by systematically exploring this relation.

The latter point is important as such knowledge can inform the development of individualized training regimes that take into account specific asymmetries in the biomechanical makeup of the athletes. The possibility of permanent assessment of such asymmetry (and, therefore, possible changes) during the training of such athletes could help achieve the desired results and reduce the risk of injury at the same time. Moreover, considering the fitness industry's current emphasis on functional training and exercise formation quality, these findings could help inform best practice guidelines for exercise programming across a variety of client demographics, from recreational sports to rehabilitative populations. In this context, the results of this study may provide a general contribution beyond a single specific improvement of general movement efficiency and effectiveness of a push-up.

1.2 Research Purpose

This study aims to:
1) **Quantify kinematic asymmetry** in push-up performance by measuring deviations in elbow and wrist joint angles.
2) **Analyse the relationship** between kinematic asymmetry and muscular fatigue.
3) **Determine** whether asymmetry increases significantly as fatigue builds, and identify its potential as an early indicator of performance decline.
4) **Explore** the implications of kinematic asymmetry for injury prevention and rehabilitation, providing a foundation for future research in this area.
5) **Investigate** how real-time feedback on kinematic asymmetries can inform training adjustments, enhancing athlete performance and safety.

1.3 Existing Studies and Research Gap

The push-up is a multiplanar exercise with the objective of incorporating upper-body strength, power, and muscular endurance (Contreras et al., 2012). Although overall load lifted is determined in part by body weight, the position of hands and feet can manipulate joint demands and activate musculature. These include, among others, activation of the pectoralis major, triceps brachii, anterior deltoid, and core musculature (Contreras et al., 2012). Changes in hand position, with narrow positioning enhancing the triceps brachii involvement and wide positioning the pectoralis major involvement, do have associated changes in muscle activation; however, there have been some findings that a narrow base of support may activate both muscle groups appropriately. Muscle recruitment is influenced by torso position relative to the hands (Gouvali & Boudolos, 2005), with more pectoralis major recruitment in the forward torso position. On the other hand, the higher the feet, the greater the load relative to a basic push-up (Ebben et al., 2011), and knee push-ups lessen it. In particular, unstable surfaces such as stability balls and BOSU balls can lead to further recruitment of stabilizer muscles, especially when the hands are placed on an unstable surface (Lehman et al., 2006; Marshall & Murphy, 2006). Aerobic variations, such as clapping push-ups, result in greater muscle activation; these movements also produce greater spinal loading (Freeman et al., 2006). In practice, it should be the job of the practitioner to balance individual needs/goals with variation choice in order to achieve maximal training effect with minimal injury risk.

Push-ups are a widely practiced and diverse strength training and rehabilitation exercise. The researchers conducted a systematic review assessing the effect of vitamin D on infection rates in healthy older adults which were compiled from kinetic data from 26 studies and 46 push-up variations (Dhahbi et al., 2018). Their findings highlighted that the load borne by the arms during elbow flexion was greater (8–21% BW) than during elbow extension (Giancotti et al., 2018; Gulmez, 2016; Mier et al., 2014; San Juan et al., 2015; Suprak et al., 2011). Yes, the force supported by the extended limbs directly measured, varied significantly, ranging between 19% BW in suspended push-ups and as high as 73% BW in posterior/inferior push-ups. (Gouvali & Boudolos, 2005; Gulmez, 2016). The type of push-up also showed that peak ground reaction forces differed, with magnitudes ranging from 29% BW in anterior push-ups to 131% BW in the standard countermovement push-up (Gouvali & Boudolos, 2005; Hogarth et al., 2013). Some of these include variations of plyometric exercises that induce significantly different impact force and rate of force development profiles (Dhahbi et al., 2017; Garcia-Masso et al., 2011; Koch et al., 2012). For joint kinetics, the highest maxima of elbow flexion moment occurred in fast and adducted hand position push-ups (Chou et al., 2011). Significantly, the highest compressive forces at the vertebral joints were created via suspended push-ups (Beach et al., 2008; McGill et al., 2014). Few studies have established dominant limb asymmetry with peak forces and rate of impact force during plyometric push-ups (Koch et al., 2012), but there have been inconsistencies regarding intercourse-related differences for kinetic parameters (Ebben et al., 2011; Hinshaw et al., 2018; Mier et al., 2014).

The systematic review and meta-analysis conducted by Zandbergen et al. (2021) aimed to synthesize the literature that has examined the effects of running fatigue on changes in running kinematics, with special emphasis on how these changes may increase the risk of running-related injuries. By synthesizing evidence across 33 articles, the authors concluded that fatigued runners, compared to non-fatigued runners, run with a less stiff gait, as indicated by greater peak tibial acceleration and greater knee flexion at initial contact and during the swing phase. However, vertical CM displacement increases only in novice runners, indicating critical inter-individual variability in the response to fatigue. The authors further add that subject-specific analyses should be employed in future analyses, as group-level analyses can obscure the responses of individual participants. Zandbergen et al.'s current study fills an important gap and is really informative, yet some research gaps are still not addressed. The lack of standardization of study design, participant characteristics, and fatigue protocols leads to heterogeneous fatigue effects on kinematic variables. Apparent also is the evidence that existing reviews have synthesized regarding kinematic changes, which do not address expected magnitudes of changes following a fatigue protocol. Furthermore, the combined conclusions of the findings could be affected by confounding effects due to the different running backgrounds of the participants. More specific systematic reviews and meta-analyses focused on the effect of fatigue and subject characteristics are required to broaden knowledge about kinematic shifts due to running-inferred fatigue and, additionally, its effect on overuse injuries.

A study by Borgia et al. (2022) investigated the effects of fatigue on running mechanics in healthy older runners versus their younger counterparts. This study shows how fatigue alters biomechanical performance across the ages. Thirty volunteer subjects were used, fifteen young and fifteen older, all experienced runners, running at least 15 miles a week. The researchers then assessed running kinematics using a 10-camera motion capture system in rested and maximal exertion exercise test conditions. There was no age × fatigue interaction; however, young runners had a larger peak knee extension moment and maximum knee power than older runners. Maximum hip power was higher for older runners. This resulted in reduced knee range of motion and greater hip extension moment in both young and old after exertion. These findings suggest that while older senior runners show different knee and hip mechanics, the gait adaptations to fatigue are similar to younger runners when controlling for running volume (Borgia et al., 2022). Though these results shed light on some of the gaps, there are several research gaps that need to be addressed in the longer term, including further study on long-term outcomes of the biomechanical alterations associated with the risk for injury, particularly in the older adult population. These psychological aspects of fatigue and their effect on running mechanics require more investigation. Future studies with larger samples of different age and race backgrounds will be required to fully quantify the nature of the individual responses to fatigue. Also, the investigation of training stimuli that may diminish the effects of fatigue on running kinematics may be of interest to both recreational and elite runners.

1.4 Significance of the Study

This study presents a real-time and quantitative measurement of kinematic asymmetry in push-up performance by utilizing advanced pose estimation technology. The study helps in developing injury prevention measures by correlating muscular fatigue and asymmetry, enabling trainers and athletes to detect performance decline at earlier stages. It is

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important to understand how these dynamics vary when generating training regimens tailored to the biomechanical demands of each athlete, thereby improving their overall performance.

In addition, this study connects biomechanics to bioengineering with direct relevance to the devices used to assess fitness in healthy athletes and people across the spectrum from active rehabilitation to rehabilitation. The study emphasizes the need for maintaining proper form during exercises to prevent injuries, supporting safer practices in exercise by examining kinematic asymmetry in relation to muscle fatigue and increasing clinical understanding of asymmetry measures in relation to fatigue using diverse as well as controlled testing environments.

Dynamic assessment of kinematic asymmetry may allow more appropriate feedback systems to be applied during the training process, increasing the adherence of the athlete to corrective strategies. In short, this research might bring about a shift in paradigm for athletes and coaches training, where movement quality could stand at the same level as performance metrics in training programs.

2. Methodology

1) Participants

The study was done through a group of volunteers who consented to participate in the study. All participants were informed about the study prior to data collection. Public data was also used, with permission taken beforehand. A total of over 1,000 datasets were used during the research, allowing for a deep and accurate analysis. Participants were selected randomly, and they were instructed to continue performing push-ups until they could no longer maintain proper form.

2) Data Collection

Data was collected using a custom-built push-up pose estimation tool that uses computer vision to its advantage to collect data. The tool was developed in Python, utilizing libraries such as OpenCV and Mediapipe. This tool allowed real-time tracking and measurement of joint angles during the exercise. The following outline the data collection process:

a) Video Recording: Participants performed push-ups while being recorded. The input video file was processed frame by frame to extract landmarks.
b) Pose Estimation: The Mediapipe library was used to detect points on the body. The written code conducted the following steps:
   - Identify points for the left and right elbows and wrists.
   - Calculate the coordinates of these landmarks for asymmetry analysis.
c) Data Logging: Each repetition of the push-up was monitored, and the corresponding joint angles were stored in a structured data format. The following were recorded:
   - Elbow angles for both sides (Elbow_Left, Elbow_Right).
   - Wrist angles for both sides (Wrist_Left, Wrist_Right).
   - A count of repetitions performed.
d) Data Storage: The collected data was saved to a CSV (excel) file for further analysis.

3) Data Processing

Once the raw data was collected, further processing was done to analyse the results. The data was analysed using a separate tool written in Python, which utilized libraries such as Pandas, NumPy, and Matplotlib. The processing steps are as follows:

a) **Data Analysis**: The logged data was imported into a Pandas Data Frame, allowing for manipulation and visual analysis. The following computations were performed:
   - Calculate asymmetry scores for both elbow and wrist by determining the absolute differences between the left and right-side measurements.
   - Compute an average asymmetry score for each repetition.
b) **Graphical Representation:** Matplotlib was used to plot the trends in asymmetry over the repetitions. This visualization provided insights into how asymmetry changed with increasing muscular fatigue.

4) Equipment and Tools

The study used the following tools and technologies:

- **Programming Language**: Python
- **Libraries**: OpenCV for video processing, Mediapipe for pose estimation, Pandas and NumPy for data manipulation, and Matplotlib for data visualization.
- **Video Recording Equipment**: Standard video camera setup for capturing movements.

3. Results

The analysis of the collected data revealed significant insights into the relationship between kinematic asymmetry and muscular fatigue during push-ups. Over the course of the repetitions, there was a notable increase in both wrist and elbow asymmetry, indicating that as fatigue sets in, participants struggled to maintain symmetrical movement patterns.

1) Data Overview

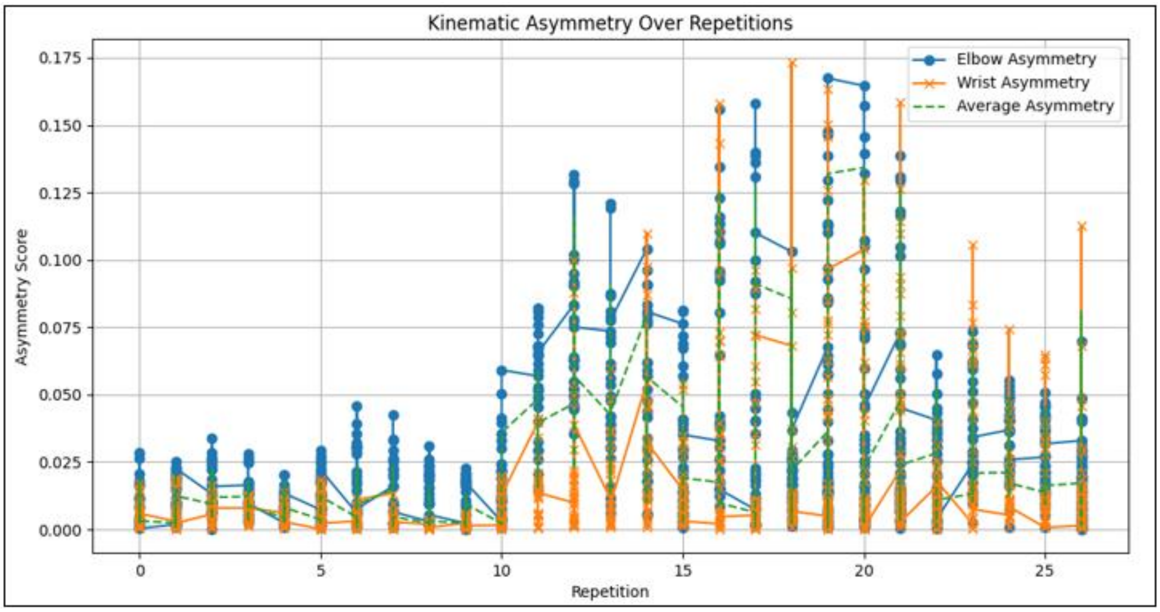
From the analysis of over 1,000 data points collected, key metrics were derived that showed the trends in kinematic asymmetry. The mean elbow and wrist asymmetry scores were calculated for each repetition, allowing for a clearer understanding of how these values fluctuated as fatigue intensified.

2) Increased Asymmetry Trends

The results showed a consistent upward trend in asymmetry scores throughout the push-up sets. Specifically, the elbow asymmetry scores showed a significant increase as repetitions progressed, with average values rising from an initial low to a peak as muscle fatigue became more pronounced. The wrist asymmetry followed a similar pattern, indicating a correlation between muscle fatigue and the ability to perform the exercise symmetrically.

- **Muscle Fatigue:** As muscles tire, they may not let out equal force on both sides of the body, leading to compensatory movements that result in greater asymmetry. This phenomenon was clear in the data, as participants displayed increasingly pronounced discrepancies in joint angles between the left and right sides.
- **Decreased Control:** Fatigue may damage neuromuscular control, making it more difficult to

maintain proper form and technique during push-ups. This loss of control was reflected in the increased variability of the data, with participants showing greater alteration in elbow and wrist angles as fatigue set in.



3) Correlation Analysis

To further investigate the relationship between muscular fatigue and kinematic asymmetry, correlation analyses was performed using linear regression. The slope and R-squared values provided understanding into how much the asymmetry scores related with the number of repetitions completed.

Elbow Asymmetry Correlation:

- Linear regression analysis indicated a strong positive correlation between the number of repetitions and elbow asymmetry scores. This trend reflects a progressive decline in bilateral control as fatigue increases, leading to uneven force exertion on each side.
- **Wrist Asymmetry Correlation:** A moderate correlation was observed for wrist asymmetry. While fatigue impacts wrist stability, the effects are less pronounced compared to elbow asymmetry, likely due to the wrist's smaller range of motion during push-ups.

4) Visual Representation

The data was visualized through graphs that illustrated the trends in elbow and wrist asymmetry across repetitions. The plots clearly depicted the increasing asymmetry scores, with the average asymmetry line demonstrating a consistent rise as fatigue accumulated.

The graphs served as a strong visual representation of the findings, showing participants' increasing difficulty in maintaining symmetrical movement patterns. The clear upward trajectory of the asymmetry scores over time underscores the potential implications for training and injury prevention strategies.

4. Discussion

The findings of this study provide insights into the relationship between kinematic asymmetry and muscular fatigue during push-ups. The results indicate a clear trend of increasing asymmetry in both elbow and wrist joint angles as fatigue piles up. This section will discuss the implications of these findings, their relevance to training and injury prevention, and potential areas for future research.

4.1 Implications for Training and Performance

The found rise in kinematic asymmetry as fatigue increases suggests that maintaining proper form during push-ups becomes more challenging as muscles tire. This can lead to uneven muscle development and increased risk of injury. For example, if one side of the body consistently compensates for fatigue by altering joint angles, this could result in overuse injuries, or extreme imbalances over time.

The strong positive correlation between elbow asymmetry and repetition count highlights the importance of watching elbow joint angles during push-ups. Since the elbow is the primary join involved in the exercise, its asymmetry may server as an early indication for fatigue. Trainers could possibly use this information to create and design more effective and personalized training programs that integrates real-time feedback on joint angles, allowing athletes to adjust their form before fatigue leads to extreme asymmetry.

Additionally, the moderate correlation for the wrist asymmetry proposes that while wrist stability is less affected by fatigue compared to the elbow, it still plays an important role in maintaining overall movement symmetry. This finding indicates the need for exercise that strengthen wrist stability, specifically for athletes who perform repetitive upper-body movements.

4.2 Implications for Injury Prevention

The relationship between kinematic asymmetry and muscular fatigue could possibly have important implications for injury prevention. Asymmetrical movements can place uneven stress on joints and muscles, increasing the risk of overuse injuries like tendinitis or muscle strains. By finding

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asymmetry early on, athletes can take proper measures to reduce injury risk.

For example, the data suggests that asymmetry scores increase fundamentally after a certain number of repetitions, indicating a threshold at which fatigue begins to impair movement quality. This threshold could be used to establish guidelines for when to stop or change an exercise to prevent injuries. The findings additionally support the use of real-time feedback systems, such as the custom push-up pose estimation tool developed for this research, to watch and monitor asymmetry during training sessions and any type of exercise.

5. Limitations of the Study

While this study provides valuable information and data, it is not without limitations. First, the sample size, although large for the current research (over 1,000 datasets), was limited to a specific demographic of participants, and may not be as accurate as hoped for. Future studies should include a more diverse population, including individuals of different ages, fitness levels, and athletic backgrounds, to determine how these factors influence kinematic asymmetry and fatigue.

Second, this research focused solely on push-ups, which are a specific type of upper-body exercise. While the findings are important for push-up performance, they may not generalize to other exercises or movements. Further research could study a larger variety of exercises and their kinematic asymmetries, such as pull-ups, bench presses, or even lower-body movements like squats, to provide more comprehensive understanding of fatigue-related asymmetry.

Finally, the study relied on a custom-built pose estimation tool, which, even if it was effective, may have limitations in terms of accuracy and precision, as it was made using public packages and applications, and aren't as accurate as medical grade technologies. Future studies could incorporate additional sensors, such as electromyography (EMG) to measure muscle activation, or force plates to assess ground reaction forces, to provide a more detailed analysis of fatigue and asymmetry.

6. Future Research Directions

This study opens several possible further researches. One possible direction is the development of real-time feedback systems that use pose estimation technology to monitor kinematic asymmetry during training. These kinds of systems could provide immediate feedback to athletes, allowing them to adjust their form and reduce the danger of injury. Future studies could also investigate the long-term effects of kinematic asymmetry on muscle development and injury risk, particularly in athletes who perform upper-body movements.

Another possible area of interest is the role of individual differences in kinematic asymmetry. For example, some participants in this study showed larger asymmetry than other participants, even at similar levels of fatigue. Understanding the factors that contribute to these differences, such as muscle strength, flexibility, or previous injury history, could help trainers develop more personalized training programs.

Finally, future research could explore the relationship between kinematic asymmetry and other types of fatigue, such as mental or cardiovascular fatigue. While this study only focused on muscular fatigue, it is possible that other forms of fatigue could also impact movement symmetry, specifically in endurance athletes or individuals performing complex motor tasks.

7. Conclusion

This study investigated the relationship between kinematic asymmetry and muscular fatigue during push-ups, using a custom-built pose estimation tool to track join angles in real time. The results showed a significant increase in both elbow and wrist asymmetry as participants conducted repetitions, indicating that fatigue impairs the ability to maintain symmetrical movement patterns during the exercise. These findings have important significance for training, performance, and injury prevention, specifically in the context of real-time feedback systems and personalized training programs.

The firm correlation between elbow asymmetry and repetition count suggests that elbow joint angles may provide early indication of fatigue, while the moderate correlation for wrist asymmetry highlights the importance of wrist stability in maintaining overall movement quality. These observations could be used to develop and create more effective training programs that incorporate real-time feedback on joint angles, allowing participants and athletes to adjust their form before fatigue leads significant asymmetry.

While this study provides valuable observations, it also highlights the need for further research and studying into the factors that contribute to kinematic asymmetry, including individual differences, exercise type, and other forms of fatigue. Further studies could explore these areas in more detail, using more advanced measurement techniques and a more diverse participant population.

In conclusion, this study contributes to the growing body of research on kinematic asymmetry and its relationship to muscular fatigue, providing a foundation for further studies in this specific area. By learning and understanding how fatigue impacts movement symmetry, anyone would be able to develop more effective strategies to improve performance, reduce injury risks, and optimize training outcomes and planning. Furthermore, it lays the groundwork for future exploration of kinematic asymmetry, aiding in developing effective training and rehabilitation strategies.

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