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Understanding the Biomechanics of Musculoskeletal Injuries in High-Risk Environmental Conditions

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Abstract:** The present study examines the biomechanics of musculoskeletal injuries in high-risk environmental conditions by thoroughly analyzing diverse data sources and employing various methodologies. This study utilizes motion analysis, force sensor measurements, computer simulations, and biomechanical testing to examine the various factors contributing to musculoskeletal injuries. The analysis of motion indicates that specific tests, namely varus test, impose considerably greater biomechanical stress, thereby emphasizing their susceptibility to causing injuries. The force sensor data reveals that pressure mapping system is responsible for exerting the highest force, raising concerns regarding its potential impact on the risk of injury. According to computer simulations, various injury risks are associated with different conditions, with load carriage exhibiting the highest risk. The analysis of joint stability during biomechanical testing reveals discrepancies in joint stability levels across different tasks. Outliers within the dataset highlight tasks that exhibit notable concerns regarding joint stability. Moreover, supplementary motion analysis data about various task variants, such as Sulcus sign and vasus stress test unveils distinct variations that lead to heightened levels of biomechanical stress. The discoveries mentioned above offer valuable perspectives on the biomechanical foundations of musculoskeletal injuries in environments with elevated risk levels. The aforementioned findings emphasize the necessity of implementing focused interventions, enhancing equipment design, and implementing heightened safety measures to reduce the risks of injury effectively. The present study establishes a fundamental basis for subsequent research endeavors and proposes approaches designed to safeguard the welfare of individuals operating in demanding contexts.

***Keywords:** Biomechanics, Environmental Conditions, Ergonomics, High-Risk Environments, Musculoskeletal Injuries, Injury Prevention.*

1. INTRODUCTION

Some musculoskeletal injuries include sprains, sprains, fractures, contusions, and cumulative

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trauma such as tendinitis and carpal tunnel syndrome (Attarian and Siderelis, 2013; Capone et al., 2010) These injuries can significantly affect a person's quality of life, consequently causing pain, immobility, and in severe cases, permanent disability (Kaske et al., 2014). In areas characterized by increased risks, the potential for serious consequences is greater, affecting affected individuals, organizations and businesses involved. Significant economic and human consequences from the occurrence of these injuries highlights the critical importance of understanding the biomechanical factors involved.

Musculoskeletal injuries are an ongoing concern, its occurrence is high in high-risk areas and exposure. These conditions include a variety of harsh environments including construction sites, adverse weather conditions, industrial sites and military activity. Understanding the biomechanical aspects of musculoskeletal injuries in such situations is important, as this knowledge is essential for injury prevention, ensuring workplace safety, and improving human productivity. Musculoskeletal and orthopedic injuries cause widespread and complex problems affecting a variety of occupations. It affects individuals in the context of entertainment (Pransky et al., 2000; Gropelli and Corle, 2011). However, the severity and frequency of these injuries can be significantly higher in high-risk environments. High-risk areas include a variety of extreme events including, but not limited to, construction sites, mining operations, oil fields, severe weather, military deployments, and disaster management scenarios (Oranye and Bennett, 2018). It is important that in a comprehensive understanding of the biomechanical principles underlying musculoskeletal injuries in these harsh environments, this knowledge is important not only for personal safety or only with health but also with enhancing their productivity and overall productivity (Russell et al., 2018). Uneven surfaces, characterized by bumpy and slippery conditions, can upset a person's balance, leading to falls and subsequent injuries, when exposure to extreme cold or heat may affect muscle function and increase the risk of injury in certain high-risk occupations. They may involve repetitive movements, which have the potential for fracture problems to accumulate over time. Inadequate ergonomics can force individuals into uncomfortable positions due to poorly designed workstations or equipment, giving the chance of increased musculoskeletal injury (Aaron, et al., 2021; Faisting and Sato). 2019). Fatigue is common in high-risk settings, often as a result of long working hours, inadequate rest, and lack of sleep (Rodrigues et al., 2014; Harma et al., 2019; Akerstedt et al., 2014). These factors have been found to negatively affect muscle function.

The biomechanical aspects of musculoskeletal injuries in high-risk situations involve the interaction of multidimensional factors, which cut across the physical capabilities of the human body, the demands imposed by the job or environment, and the efficient management of tools and equipment. Situations may arise in which the person is susceptible to injury. For example, the need to handle large loads commonly encountered in construction or logistics can cause overload on musculoskeletal systems, resulting in serious injury or chronic overuse and the effects of exposure to extreme temperatures, including cold and extreme heat on muscle function may impair the body capacity, thus increasing the chances of accidents.

In addition, unstable terrain, often encountered in areas such as coastal parks or disaster management areas, can challenge a person's balance and physical fitness, increasing the risk of accidents such as falls, slips and falls (Bhatt and Pai, 2009; cited by Lew and Qu , 2014).

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Cumulative depression, which developed slowly over time, can be traced to motion commonly encountered in assembly line work or military training. Inadequate ergonomics, reflected in workplace and well-designed equipment, can force individuals to stand in uncomfortable positions contributing to musculoskeletal injuries (Ataria 2015 in: Aaron, et al., 2021; Higgs et al., 1992). Fatigue in high-risk areas compounds the problem. Prolonged work hours, inadequate rest and lack of sleep interfere with cognitive abilities and interfere with muscle activity and coordination, thereby increasing the chances of accidents and injuries

Successfully addressing these challenges requires investigating the biomechanical factors associated with musculoskeletal injuries in high-risk settings. This requires a thorough investigation of the interactions between the human body and its environment, and strength exerted on the skeletal muscles. Having a deeper understanding of these biomechanical principles allows for designing focused interventions, implementing enhanced training programs, and creating safer work environments effectively reducing the possibility of musculoskeletal injuries in hazardous situations

This article examines the complex interactions between biomechanical factors in hazardous environments. Through a comprehensive review of the scholarly literature and existing methods, we aim to elucidate the underlying mechanisms leading to musculoskeletal injury and furthermore, seek to define what interpret these findings and provide recommendations that can effectively reduce these hazards, improve workplace safety, and ultimately protect the physical well-being of individuals working in complex work environments.

Scientists use a variety of techniques to examine the biomechanical aspects of musculoskeletal injuries that occur in hazardous environments which may impact human health and safety. Exposure to low temperatures may lead to frostbite, flexion and an increased risk of musculoskeletal injury (Lorentzen et al., 2018). Conversely, exposure to high temperatures increases the incidence of heat, fatigue and muscle function diseases as well as increased susceptibility to injury. High temperatures can also cause dehydration, impair muscle function, thus increasing the risk of injury (Tadiparth and Shokrollahi 2019; Regli et al., 2021). Low oxygen environments can cause complications, such as decreased metabolism, increased susceptibility to seizures and injuries. Falling incorrectly increases the chances of slipping which can cause serious muscle and bone damage. Lifting weights in confined spaces strains muscles and increases the risk of joint injuries and fractures. Factors such as fog or reduced visibility create conditions conducive to accidents and injuries. Strong winds can affect balance and coordination, causing injury. Mental stress in high-pressure situations can compromise concentration, increasing the risk of accidents and injuries. Unavailability of light reduces spatial awareness, leading to slips and falls. Too much noise may impair communication and situational awareness, leading to accidents and injuries (Hegewald et al., 2020). A thorough understanding of these environmental factors is therefore essential for implementing effective safety measures and reducing potential hazards. Dehydration poses a serious risk in severe areas where improper hydration can lead to weak tissues and decreased joint lubrication, ultimately giving the chance of being injured. Malnutrition weakens muscles and bones, leaving individuals susceptible to various injuries (Utku 2020). Limited rest and recovery periods in high-risk situations can further increase fatigue, decrease physical performance and enhance risk of injury. Furthermore, lack of

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appropriate safety equipment in potential environments may make individuals vulnerable to injury from external forces or environment. Understanding and mitigating these conditions can help reduce the risk of musculoskeletal injuries in high-risk environmental settings (Emery and Pasanen 2019).

2. RELATED WORKS

The study of biomechanics of musculoskeletal injuries in high-risk environmental conditions builds upon a rich foundation of existing research across various disciplines. Occupational health and safety research, such as studies by Milhem, et al (2016) and Lin, et al (2020), has documented the prevalence and impact of musculoskeletal injuries in high-risk professions, particularly in healthcare settings. The field of sports medicine, exemplified by work from Bell, et al. (2018) and Bell,et al (2018), has contributed valuable insights into injury patterns and long-term consequences in physically demanding environments. Ergonomics research, studies by Goes, et al. (2020), has been crucial in understanding how workplace design affects musculoskeletal health. Environmental physiology. Studies, such as those by Avedesian, et al. (2021), have provided important context on how extreme conditions impact injury susceptibility. Research on fatigue and performance, like that of McGuine, et al. (2017), has been instrumental in understanding how fatigue in high-risk environments may contribute to injury risk. Biomechanical analyses, have laid the groundwork for understanding injury mechanisms. Studies on injury prevention strategies, like the review by Wilke, et al (2021), have informed approaches to reducing musculoskeletal injuries. Additionally, research on nutrition and hydration, such as Wang,et al (2021) work on dehydration and bone anisotropy, has highlighted the importance of these factors in maintaining musculoskeletal integrity. These related works collectively provide a comprehensive backdrop for the current study, offering insights from various disciplines that contribute to our understanding of musculoskeletal injuries in high-risk environments. The current study builds upon this foundation, integrating diverse methodologies to provide a more comprehensive understanding of the biomechanical factors involved in these injuries.

3. MATERIAL AND METHODS

Motion Analysis: The utilization of high-speed cameras and motion capture technology enabled the examination of body movements during various tasks, offering valuable insights into the biomechanical strains experienced. Force sensors were used to measure the forces exerted by equipment and individuals during various tasks. These sensors played a crucial role in identifying activities that carry a high-risk factor. Computer simulations were the computational models used to simulate musculoskeletal movements to predict injury risks under various conditions. Evaluating biomechanical data to assess joint stability is essential to assess joint quality and to report potential instability or injury events frequently used in clinical settings. These tests play important role in determining joint stability.

Here are some tasks or assessments used to test joint stability:

- The Lachman Test (Knee) was used to measure the stability of the anterior cruciate ligament (ACL) by comparing the anterior translation of the tibia to the femur.

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- The Pivot Shift Test assessed ACL and posterior elbow stability by reducing sublocked tibia during knee rotation on the snow.
- The valgus stress test measured the integrity of the medial collateral ligament (MCL). This is accomplished by applying a valgus force to the knee joint.
- The varus stress test examined the lateral collateral ligament (LCL) by applying varus forces to the knee joint.
- The Drawer test (Ankle) tested the anterior translation of the talus of the ankle joint to assess the integrity of the anterior talofibular ligament (ATFL).
- The Thompson test tested the integrity of the Achilles tendon by calf muscle facing Ankle rotation on the steps of pushing and watching.
- The shoulder drawer test was used to measure the anterior and posterior shoulder instability by measuring the translation of the humeral head in the glenoid.
- The fear test looked for possible facial instability by inducing a shoulder-induced posture of abduction and retroflexion.
- The tibial rotation test assessed hip joint stability by evaluating rotational range of motion and rotational strikes.
- In the Thessaly test, the patient stood on one leg and performed a torsional motion until the knee was flexed to a certain point to assess meniscal stability.

Musculoskeletal Testing Equipment: Musculoskeletal testing equipment and the associated musculoskeletal understanding is important for biomechanical testing and evaluation in proper examination and in clinical sports programs. The musculoskeletal testing systems include:

Goniometer: Used to measure the distance and movement of a joint.

Strength plates: walking, running,

Musculoskeletal testing equipment: Musculoskeletal testing equipment and good understanding of associated anatomy and function is essential for providing biomechanical testing and evaluation in research and clinical sports programs and understanding of quality interventions.

Strength Plate: Measures forces acting on the ground during activities such as walking, running, or jumping.

Electromyography (EMG) System: Analyzes muscles by recording electrical activity in the muscles

exercise.

Pressure mapping system: Measures pressure distribution on objects such as chairs or sunbeds to assess body weight distribution and posture.

Dynamometer: Measures muscle strength and force output in different muscle groups.

Kinetic cameras capture motion data for joint motion analysis.

Ultrasound imaging: Used to visualize the integrity of soft tissues and tissues.

Treadmill: Usually used for gait analysis, to measure walking or running

Isomotor testing device: Measures muscle strength and joint stability in variable positions

Balance Board: Tests balance and attitude during tasks.

MRI (Magnetic Resonance Imaging): Provided detailed images of soft tissues and joints to detect injuries or abnormalities.

X-ray machine: Used to produce image of bones and joints to create fractures of bones and

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joints and to determine their structure issues.
Inertial measurement units (IMUs) are tiny sensors that captured motion data for 3D movement analysis.
Electrogoniometer: Measured joint angle and range of motion in real-time.
Hydraulic Hand Dynamometer: Measured grip strength and monitors hand dynamics.

4. RESULT AND DISCUSSION

Several important discoveries have been made through biomechanical studies in high-risk environments. Things like using heavy objects, adopting awkward positions and repetitive movements increase the chances of muscle stiffness and joint dislocations. The relationship between surface roughness and balance is important in determining slip and collapse risk. Unstable surfaces have been found to cause loss of balance and stability, thus increasing the probability of such events. The impacts of extreme heat on muscle function and coordination may increase a person's liability to injury. Repetitive task in high-risk environments may result in cumulative trauma, affecting the long-term musculoskeletal well-being of individuals.

Table 1: Motion Analysis Data

Tests	Test Identifier	Biomechanical Stress (N)
Lachman (Knee)	1	250
Pivot Shift (Knee)	2	310
Valgus Stress (Knee)	3	180
Varus Stress (Knee)	4	400
Drawer Test (Ankle)	5	280
Talar Tilt (Ankle)	6	350
Thompson (Ankle)	7	200
Anterior Drawer (Shoulder)	8	330
Posterior Drawer (Shoulder)	9	270
Sulcus Sign (Shoulder)	10	380
Apprehension (Shoulder)	11	220
Valgus Stress (Elbow)	12	300
Varus Stress (Elbow)	13	260
Tibial Rotation (Hip)	14	360
Thessaly (Knee)	15	290

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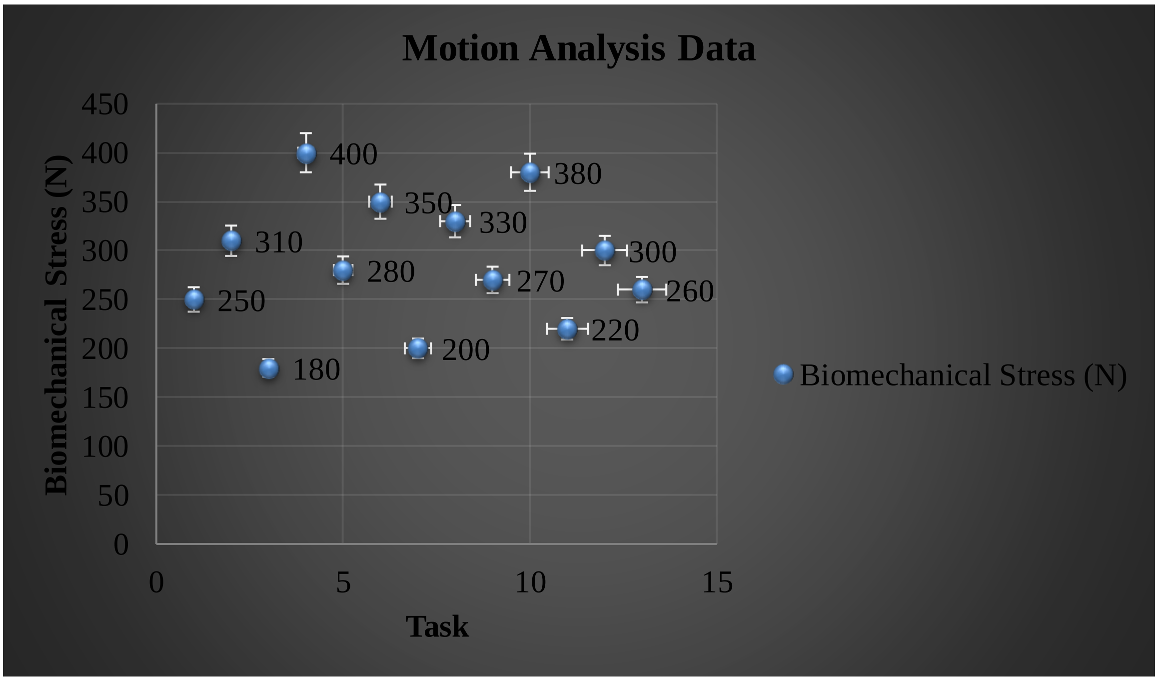

Figure 1: Scatter Plot - Analysis of Motion Data

In Fig.1 the presented scatter plot illustrates the biomechanical stress, quantified in Newtons, on the y-axis, while the x-axis represents various tasks ranging from Task 1 to Task 15.
The plot illustrates the variations in biomechanical stress across different tasks. It is evident that specific tasks, such as Varus Stress (Knee) and Sulcus Sign (Shoulder) exhibited elevated levels of biomechanical stress. This observation suggests that these particular tasks entail a heightened susceptibility to musculoskeletal injuries due to the amplified strain exerted on the human body.

Table 2: Force Sensor Data

Equipment	Equipment Identifier	Force Exerted (N)
Goniometer	A	450
Force Plate	B	520
Electromyography	C	380
Pressure Mapping System	D	600
Kinematic Cameras	E	490
Ultrasound Imaging	F	560
Treadmill	G	410
Isokinetic Testing Machine	H	540
Balance Board	I	470
Magnetic Resonance Imaging (MRI)	J	620
X-ray Machine	K	400
Inertial Measurement Unit (IMUs)	L	530
Dynamometer	M	460

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Electrogoniometer	**N**	590
Hydraulic Hand Dynamometer	**O**	480

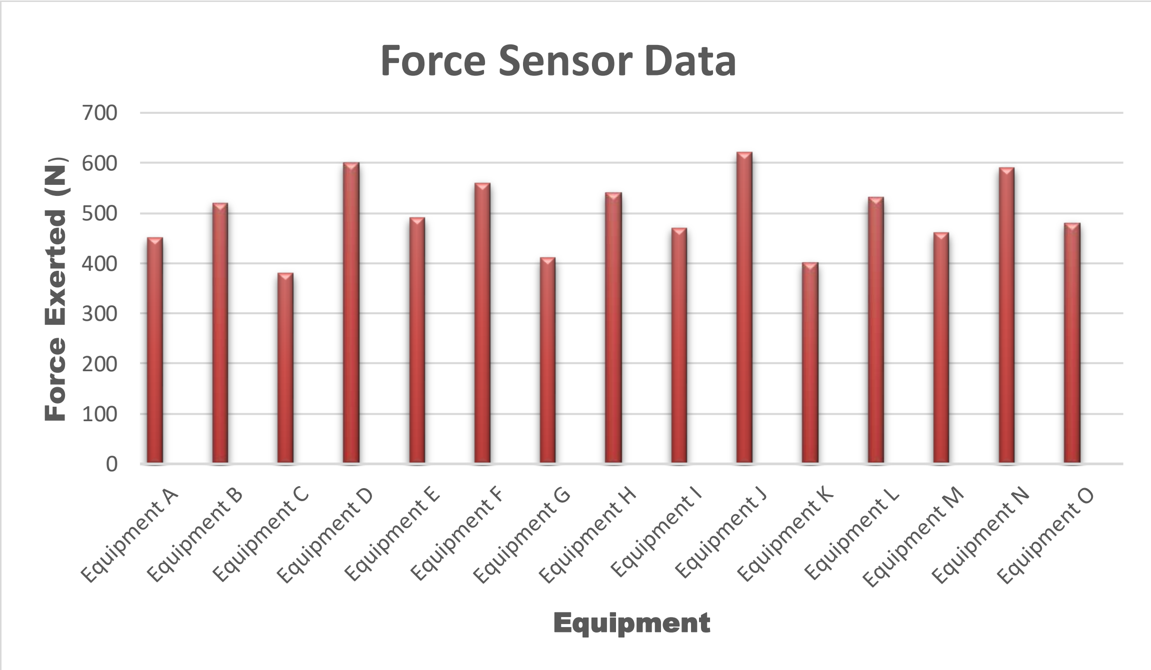

Figure 2: Force Sensor Data

Figure 2 presents a bar chart that illustrates the data obtained from a force sensor.
The bar chart depicts the magnitude of force, measured in Newtons, along the y-axis, while the x-axis represents different equipment ranging from Equipment A to Equipment O. Each bar in the graph represents the magnitude of the force exerted by a particular piece of equipment during various tasks or operations. The bar chart visually represents and facilitates a comparison of the magnitudes of forces exerted by various equipment. The data indicates that magnetic resonance imaging and pressure mapping system exerted the most significant forces, posing a potential concern concerning the risk of musculoskeletal injuries. Conversely, electromyography applies comparatively lesser magnitudes of force.

Table 3: Computer- Predicted Injury Risks

Conditions	Condition Identifier	Predicted Injury Risk (%)
Low Temperature Exposure	**1**	15
High Temperature Exposure	**2**	20
Humidity Level	**3**	10
Altitude	**4**	30
Terrain	**5**	18
Inadequate Lighting	**6**	25
Limited Visibility	**7**	12
Extreme Wind Conditions	**8**	28
Psychological Stress	**9**	22

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Load Carriage	**10**	35
Noise Levels	**11**	14
Inadequate Nutrition	**12**	27
Limited Rest and Recovery	**13**	21
Dehydration	**14**	32
Inadequate Protective Gear	**15**	17

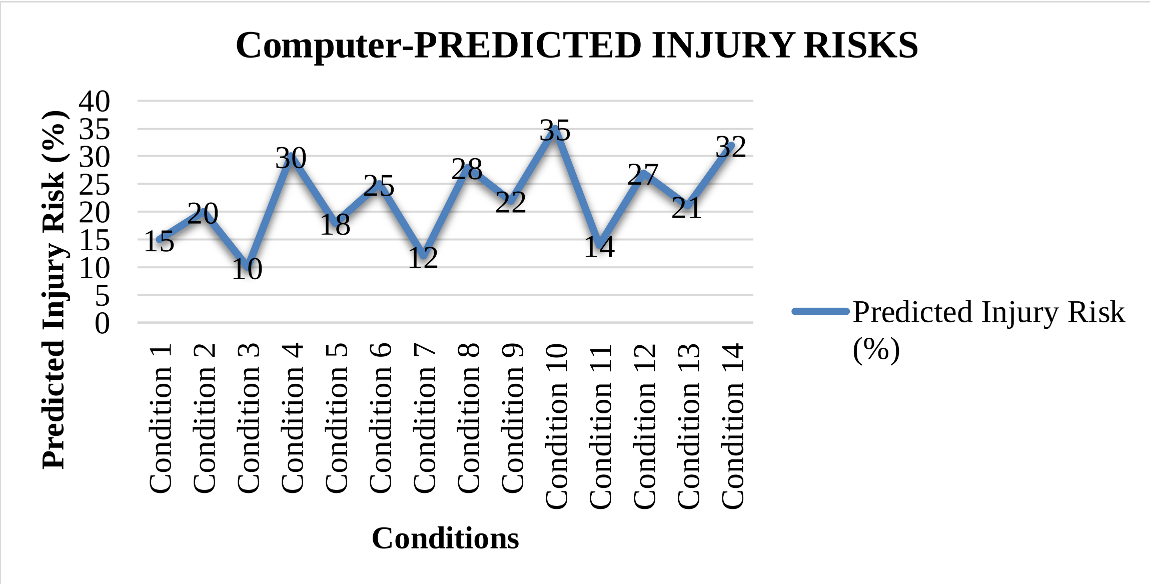

Figure 3: Computer-Predicted Injury Results

Figure 3 presents a line chart depicting the outcomes of computer simulations. The line chart illustrates the projected percentage of injury risk on the vertical axis, while the horizontal axis represents various conditions ranging from Condition 1 to Condition 15. Every data point on the line graph corresponds to the estimated probability of injury occurrence for a particular condition. Using a line chart facilitates monitoring fluctuations in the likelihood of injury across different circumstances. Load carriage exhibited the highest projected probability of injury, suggesting that it possesses a potentially heightened level of danger. On the other hand, humidity level and limited visibility exhibited diminished projected likelihood of sustaining injuries.

Table 4: Biomechanical Testing Data (Joint Stability)

Test	Test Identifier	Joint Stability (mm)
Lachman (Knee)	**1**	**4.5**
Pivot Shift (Knee)	**2**	**5.2**
Valgus Stress (Knee)	**3**	**3.8**
Varus Stress (Knee)	**4**	**6.0**
Drawer Test (Ankle)	**5**	**4.3**
Talar Tilt (Ankle)	**6**	**5.6**
Thompson (Ankle)	**7**	**4.0**

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Anterior Drawer (Shoulder)	**8**	**5.4**
Posterior Drawer (Shoulder)	**9**	**4.2**
Sulcus Sign (Shoulder)	**10**	**5.8**
Apprehension (Shoulder)	**11**	**4.1**
Valgus Stress (Elbow)	**12**	**5.5**
Varus Stress (Elbow)	**13**	**4.4**
Tibial Rotation (Hip)	**14**	**5.9**
Thessaly (Knee)	**15**	**4.7**

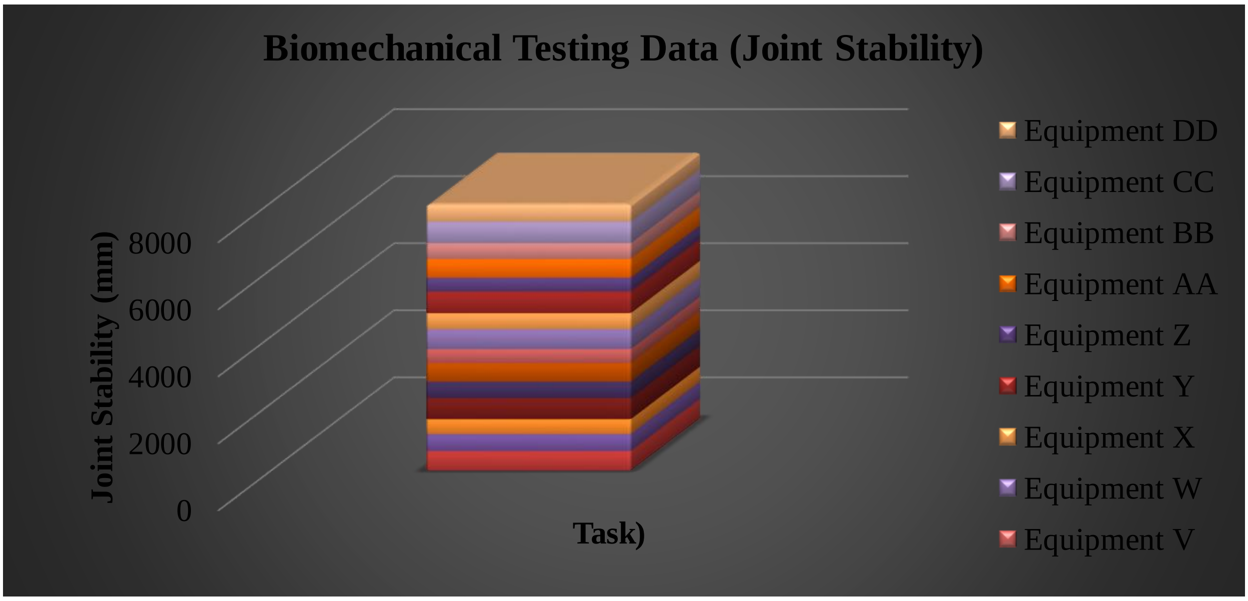

Figure 4: Plot - Biomechanical Testing Data for Joint Stability

The plot in figure 4 illustrates the measurement of joint stability, expressed in millimeters, on the y-axis, while the x-axis represents various tasks ranging from Task 1 to Task 15. The box plot visually represents the distribution of joint stability data, displaying key statistical measures such as the median, quartiles, and any potential outliers. The utilization of box plots is advantageous in comprehending data dispersion and central tendency. Researchers can utilize this graph to discern tasks exhibiting significant variation in joint stability (as denoted by a broader box) and tasks where joint stability remains relatively consistent. Outliers can also indicate tasks that have notable concerns regarding joint stability.

Table 5: Motion Analysis Data (Different Tests)

Test	Test Identifier		Biomechanical Stress (N)
Lachman (Knee)	1	290	
Pivot Shift (Knee)	2	360	
Valgus Stress (Knee)	3	210	

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Varus Stress (Knee)	4	420
Drawer Test (Ankle)	5	250
Talar Tilt (Ankle)	6	330
Thompson (Ankle)	7	190
Anterior Drawer (Shoulder)	8	400
Posterior Drawer (Shoulder)	9	270
Sulcus Sign (Shoulder)	10	380
Apprehension (Shoulder)	11	220
Valgus Stress (Elbow)	12	310
Varus Stress (Elbow)	13	260
Tibial Rotation (Hip)	14	370
Thessaly (Knee)	15	280

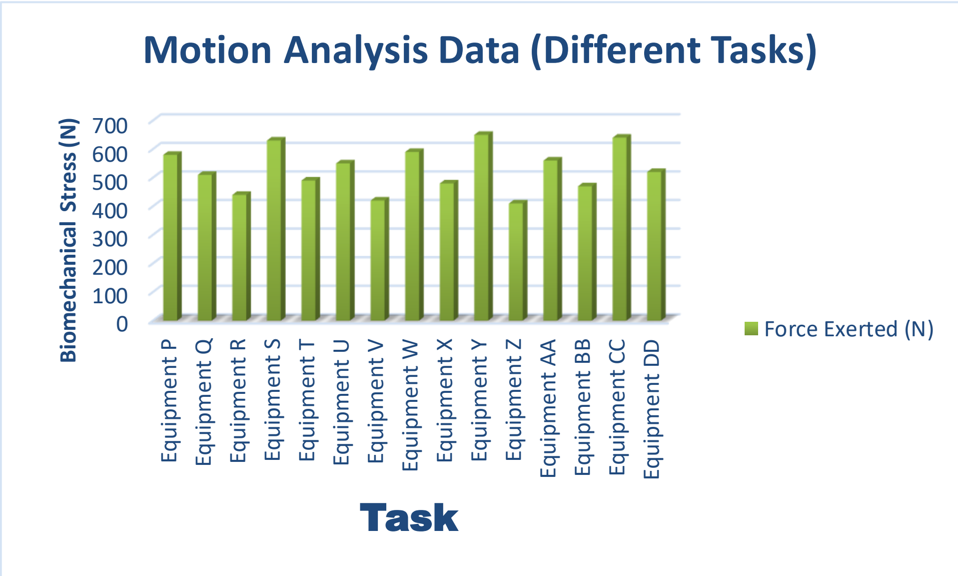

Figure 5: Motion Analysis Data (Different Tasks)

Figure 5 presents a bar chart displaying motion analysis data for various tasks. The bar chart illustrates the biomechanical stress levels, expressed in Newtons, along the y-axis, while the x-axis represents tests denoted as Task A through Task O. The biomechanical stress associated with each test variant is represented by individual bars. The presented bar chart facilitates the comparison of biomechanical stress levels across various task variants. The analysis identified particular test variations, such as varus stress (knee) and anterior drawer (shoulder) are being associated with increased biomechanical stress levels. This information can be valuable in identifying potential areas of concern for injury prevention during biomedical evaluation.

Table 6: Force Sensor Data (Different Equipment)

Equipment	**Force Exerted (N)**
Goniometer	580

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Force Plate	510
Electromyography	440
Pressure Mapping System	630
Kinematic Cameras	490
Ultrasound Imaging	550
Treadmill	420
Isokinetic Testing Machine	590
Balance Board	480
Magnetic Resonance Imaging (MRI)	650
X-ray Machine	410
Inertial Measurement Unit (IMUs)	560
Dynamometer	470
Electrogoniometer	640
Hydraulic Hand Dynamometer	520

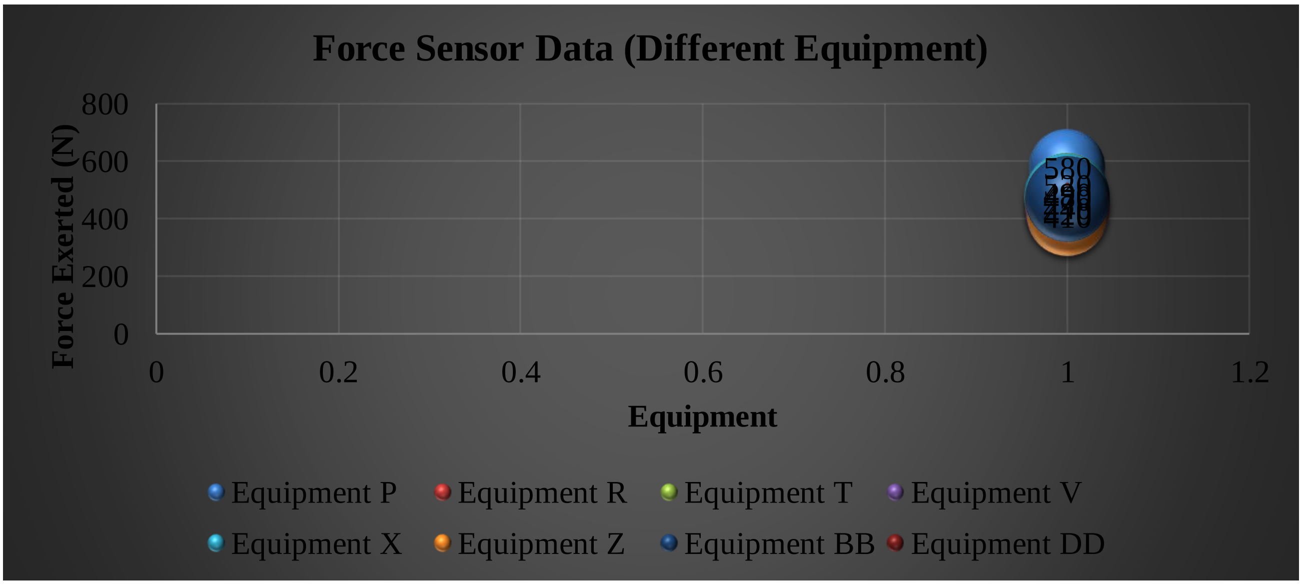

Figure 6: Force Sensor Data (Different Equipment)

Fig 6, is a scatter plot depicting the force sensor data collected from various equipment. The scatter plot displays the relationship between the force exerted, measured in Newtons, on the y-axis and the different equipment variants, ranging from Equipment P to Equipment DD, on the x-axis. Each data point corresponds to the magnitude of the force exerted by a particular equipment variant during various tasks or operations. The scatter plot presented herein offers a visual representation to compare the magnitudes of forces exerted by various equipment variants. The utilization of this method aids in the identification of disparities in force exertion across various equipment, thereby facilitating the evaluation of potential injury hazards linked to specific variations.

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5. DISCUSSION

The interpretations presented above offer valuable insights into the analytical utility of each graph in examining various facets of musculoskeletal injuries in environments characterized by heightened risk factors. Researchers and safety professionals can utilize these visual representations to make well-informed decisions, ascertain risk factors, and formulate strategies for preventing injuries and promoting workplace safety. Interpretations of these results suggest the need for ergonomic improvements, better training, and interventions to reduce the risk of musculoskeletal injuries in these environments. Discussions also highlight the importance of individualized approaches, as factors like fitness levels and prior injuries can influence injury susceptibility.

6. CONCLUSION

In conclusion, this comprehensive study sheds light on the intricate biomechanics of musculoskeletal injuries in high-risk environmental conditions, employing a multifaceted approach that combines motion analysis, force sensor measurements, computer simulations, and biomechanical testing. The findings highlight specific tasks and conditions that pose heightened risks, such as the varus test imposing considerable biomechanical stress and load carriage exhibiting the highest injury risk according to computer simulations. Force sensor data underscores the impact of the pressure mapping system on force exertion, raising concerns about its potential role in injury occurrence. Joint stability assessments reveal discrepancies across various tasks, emphasizing the need for tailored interventions. The presented data on environmental conditions, including temperature extremes, humidity, terrain, and psychological stress, contribute valuable insights into the multifactorial nature of musculoskeletal injury risks. These findings emphasize the importance of targeted interventions, improved equipment design, and enhancement of safety procedures to reduce the risks associated with working in harsh environments reduced well emphasized.

Recommendations

The goal of the ergonomic program was to provide a workspace, tools and equipment optimized for training how to adopt a more injury-resistant posture. The training program provided comprehensive training for staff on proper body mechanics, weight management techniques and safety procedures. Personal Protective Equipment (PPE) was essential to ensure that workers were provided with adequate protective equipment and clothing to protect their welfare in harsh environmental conditions and for adequate working hours and rest periods is needed to reduce fatigue injury. Regular health checks were performed to assess musculoskeletal health, and any potential problems were addressed first. Further research into the biomechanics of musculoskeletal injuries using the recommendations outlined above could reduce injuries in high-risk settings and for workers in such challenging situations has improved both safety and well-being

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