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REVIEW PAPER

An Overview of Protective Gloves with Regards to Hand Performance and the Evaluation Methods

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***Abstract*- Many tasks are carried out with the use of hands in various environments and working conditions, so protective gloves are widely utilized by workers voluntarily or as needed. The present study aims to introduce the hand, its various parts, and the importance of protecting the hands, which are subjected to several mechanical and perceptive situations. Moreover, the literature introduces the types of protective gloves, their design and structure. The factors affecting the performance of protective gloves and their evaluation methods are also included. This paper contains two parts; the first part is allocated to overview the importance of protective gloves and the second part is assigned to the published researches in each field and their results are elaborated. By probing the results of the previously conducted researches on protective gloves, it was found that wearing protective gloves often reduced the strength capability of the hand, tactile sensitivity, manual dexterity and range of motion, while the discrepancy in the results of some functions, such as pinch or torque, was observable in the studied researches. Examination of hand performance measurement tasks also showed weaknesses and shortcomings in some methods, and this was one of the causes of contradictions in the results of studies.**

***Keywords*: protective glove, strength, dexterity, sensitivity, muscle activity**

I. INTRODUCTION

Scientific advances in various fields have elevated the quality and merit of human existence. Although modern life is more comfortable and has brought welfare to humans, it may expose them to the risk of unknown physical, chemical, and biological hazards [1]. Various personal protective equipment such as vests, masks, hats, shoes and gloves are applied to protect different body sections such as the face and eyes, head, legs, hands, arms, and ears.

The human hand has the most complex anatomy in the body and it is more often used while doing different activities. Thus, hand injuries are the main sources of accidents, especially at work [2]. In developed countries, considerable range of damages is caused by occupation and the workplace [3]. According to reports by the US National Electricity Monitoring System, injured wrists and fingers are the most recorded injuries and it was declared that hand and finger troubles are more common compared to the other occupational injuries [4,5]. The risk of hand damage increases when working with tools and when joining pieces. It should be noted that the use of associated protective gloves considerably reduces the hand-related risks [6]. The use of gloves prevented injuries and significantly reduced the damages and also crush, fractures, avulsions, amputations, and dislocations [7]. Therefore, hand protection is necessary at the workplace for prevention of mechanical hazards (wear, cutting, compressing, breaking, piercing, and damaging), severe thermal hazards (heat and cold), radiation (nuclear, ultraviolet radiation, X-rays, and heat), chemical hazards, the transmission of diseases through contaminated blood, and also to provide protection against electrical hazards and vibration, and to reduce blistering, bruising and other various injuries [8].

Although wearing protective gloves reduces injuries, it may cause unwanted side effects and problems, such as getting stuck in a device during work or difficulties such as skin rash due to allergies [9]. Gloves also can affect hand performance abilities such as strength capabilities

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of the hand, range of finger and wrist movements, tactile sensitivity, manual dexterity, tiresome, and other problems during the work [10].

II. EFFECTIVE FACTORS IN THE APPLICATION OF PROTECTIVE GLOVES

Human hands may be exposed to harm or infection in the presence of many materials. One way to reduce the risk of such damages is to wear suitable protective gloves. Now, a wide variety of protective gloves are available, each of which protects hands and fingers against various dangers. It is noteworthy that the use of any kind of safety gloves would not be suitable for every work, because there are different risks associated with different jobs. Besides, it may have adverse consequences such as the transmission of contamination, causing skin problems, or affecting the correct performance of the wearer. To decide which gloves are suitable for a particular application, factors such as design, the user status, and working conditions at the workplace should be considered [11]. Factors influencing the selection of gloves cannot be considered single-dimensionally, while sometimes a combination of the criteria for the selection of gloves should be applied appropriately.

A. Design and Construction

The clothing which is regarded as a secondary skin will be appropriate to the human body, by consideration of the type of movement and its range, and in terms of ventilation and comfort [12]. Of course, it is usually more difficult to follow these tips for protective equipment, besides considering the protective function. For this purpose, the design of protective clothing should cover various factors which will be discussed below.

A.1. Thickness and Number of Layers

In some cases, gloves consisting of two or more protective layers may be designed and manufactured to improve wearers' performance. For example, astronauts' gloves which are designed to protect their hands from certain weather and environmental conditions are a set of three-layer gloves. As another example, people who are sensitive to latex may use an inner layer inside the gloves. The thickness of the materials and the design of gloves can be varied, as well. Thin and poor gloves have low protection against dangers, while thick gloves create greater resistance to chemicals or mechanical hazards. However, an increase in the thickness may result in a reduction of skill and sensitivity, thus reduces safety. Therefore, it is advisable that the thickness of the material and the number of layers used in various parts of the glove should be considered differently, depending on the situations that the hands are exposed to danger [13].

A.2. Type of Material and Its Physical and Mechanical Properties

Gloves are made from different materials depending on the type of hand protection that is anticipated, including the physical, mechanical, chemical, biological, and radiation protection. Various materials, such as cotton, nylon, leather, plastic, rubber, tarry or wire mesh, and aluminized fabric are used to make gloves. It is also possible to combine different fabrics such as woven or knitted blend fabrics, or composites of different fabric types that are produced by sewing, laminating, or bonding of different layers. Due to the required protection level, finishing operations may also be carried out on the fabrics. As an example, polyvinyl chloride, nitrile, and vinyl PVC fabrics can be mentioned [14]. The fibers used in protective gloves include elastomeric fibers such as lycra, natural fibers like wool and cotton, or regenerated fibers such as viscose rayon, flexible fibers such as nylon, silk, and polyester or non-flexible fibers such as glass or ceramic fibers. Physical and mechanical properties of protective materials such as the weight and thickness, shear strength, tear perforation and wear resistance, flexural strength, frictional properties, and pressure properties are among the important properties affecting the performance of protective equipment that should be considered [15].

A.3. Cuff

Many gloves continue to cover the wrists, so the style and length of the gloves are different depending on the purpose of the glove. To protect the hands and arms from chemical and toxic influences such as the large volume of liquid or dangerous objects that are likely to come into contact with hands, a longer cuff length for gloves should be utilized. Therefore, the length of the glove's cuffs may differ depending on the end-use of the glove.

A.4. Surface Characteristics

Most manufacturers offer flat or textured surfaces for gloves. Lumpy surface provides a better grip for hands, which is important when working in wet and oily conditions [16]. In cases where a glove with an appropriate level of friction is required, manufacturers should provide this friction with various materials such as latex or other rubbers.

A.5. Design

There are several types of gloves designed to protect the entire hand or part of it. For example, it is sometimes necessary to protect your wrists or fingers. Gloves structures consist of single and multi-layer gloves, which can be back-coated or open back gloves, gloves with one place for four fingers and one place for the thumb, double gloves, and gloves with a reinforcement pad in the palm or back of the hands or fingers [17]. Therefore, gloves are designed and constructed based on the area of the hand that needs protection and the type of work to be carried out.

A.6. Protective Properties

Depending on the different working conditions, the person may be exposed to risks such as fire, chemicals, radiation and, living organisms such as bacteria. Protective clothing can protect people from these dangers. Gloves are one of the categories of protective clothing that should be prepared and used according to the type of danger that threatens the hand. The type of utilized gloves varies depending on the hazards confronting the health of the hand. For example, in facing of chemical hazards, gloves should be compatible with hand-held materials to prevent gloves from being damaged. Additionally, the glove materials should be compatible with the skin and do not cause allergies. Another type of hazard that threatens the hand is physical hazards, including abrasion with hard and harsh parts, perforations, impacts, and heavy forces. One of the methods for increasing the protection against such hazards is to raise the number of layers in the glove, which has consequences such as diminishing the range of motion and the reduction in gloves' performance. In other words, the glove's protection level is usually in opposition to the comfort and working ability of the hand. Therefore, it is necessary to determine the level of optimal protection and provide solutions to improve the effectiveness of hands when using gloves [18].

A.7. Ergonomic Properties

The ergonomics of protective clothing is an important aspect, which needs to be considered while producing and using it. Ergonomics is a dynamic feature that is examined by considering interactions between humans and clothing [19]. The goal of ergonomics is to optimize the comfort, safety, and performance of humans when using protective clothing [20]. Clothing comfort is one of the important features of it [21]. Comfort includes the thermal, physical and, mental status and interactions between the human body and the environment. The comfort of protective clothing may change over time or under different environmental conditions. The importance of ergonomics is to minimize the loss of human performance when wearing protective clothing. The use of harsh and hard-wearing materials in the production of gloves or seams in contact with hands is one of the factors that affect the ergonomics and comfort of protective gloves. Furthermore, gloves should be made of safe and flexible materials to enable the wearer to accomplish the expected task. The weight of protective clothing is another determinant factor in its performance. The weight influences the level of muscle activity and fatigue of the individuals. In addition, it increases the energy consumption and thus heat generation. It is clear that the heat in cold climates is not troublesome, but it becomes a challenging issue in a warm, temperate, or humid environment [21].

B. Conditions for Glove Wearer

B.1. Glove Size

In the production of various protective gloves, the design features are important in determining their level of performance and protection. In this context, fitting the glove size on hand is the most important factor to keep in mind. Hence, the size of the hand and the gloves is proportional to the performance capability, comfort, and efficiency of the individuals. Fitting the size of the hand and gloves has a great impact on the performance, comfort and efficiency. In addition, gloves that are too small or large, restrict the hand movement and create fatigue in the hands and fingers. Tight gloves also cause skin problems, while very large gloves affect the hand grip. In order to prepare the suitable gloves, at the first stage, the measurements have to be done on the hand, and then the gloves must be selected with regards to the standard definition of sizes. Size can vary between manufacturers and among different types of gloves, so it is important to have a wide range of sizes available for each glove [17].

B.2. Skin Conditions

Wounds and skin lesions should be covered by dressings before wearing gloves. Skin conditions can affect the choice or use of gloves. People with eczema or allergies may need to use a thin layer of cotton inside the glove to prevent sweat irritation. People with latex allergies should not use latex gloves because of the high sensitivity to latex, thus the use of latex substitutes is recommended [17].

B.3. Comfort

Other functions aspects that should be considered while wearing gloves are their comfort or discomfort. Glove's comfort has two different aspects: one is feeling comfortable in the hands after wearing a glove, and the other is the hand condition after wearing the gloves. The comfort of the gloves affects the ease of performing a specified task. It should be noted that an optimal level of comfort and work tranquility should be made on gloves [10].

Generally, protective clothing decreases the heat dissipation and leads to consumer's discomfort. Therefore, the issue of heat and sweat is very important [22]. Manufacturers have proposed different measures for the disposal of heat and sweat from the protective clothing. For example, one of these processes is the combination of polyester and cotton fibers and the production of fabrics that have extraordinary properties in the repellency of heat and sweat. Another way to reduce and therefore regulate the heat is through using a battery or shape-memory materials. Chilled gases and liquid or phase-change materials are applied to cool the body, as well. However, using some of these materials may increase the weight and bulkiness of protective clothing and diminish the range of motion. Since comfort is a conceptual state that is sensed by individuals, it cannot be measured quantitatively, thus for this reason; researchers have proposed different ways to evaluate this feature. One of these methods is to use the convenience and discomfort assessment tables where the zero to five scales is used as below:

0=no discomfort, 1=very little discomfort, 2=low discomfort, 3=unpleasant discomfort, 4=you are upset, and 5=very severe discomfort

In addition, a five-point scale is designed to assess the ease of use, in which:

1=very easy, 2=easy, 3=normal, 4=hard, and 5=very hard

Besides, in some researches comparison method of the pairs is applied [13,23].

Time and continuity in doing work and rest periods between each job are the factors that clearly and inevitably influence all hand functions and in particular hand performance [23].

C. Working Conditions

C.1. Working Environment

The environmental and work climatic conditions may affect the performance and comfort of hands when using gloves [24]. In hot or humid weather conditions, wearing glove may lead to a lot of perspiration; however in cold weather conditions, it is necessary to observe the gloves' insulation. Therefore, when choosing a glove, it is necessary to pay attention to the climatic condition of the area, to make clear whether it is hot, dry, wet or cold. Moreover, the environmental circumstances of the workplace which can be muddy or dirty and slippery should be analyzed [24].

C.2. Kind of Work

The type of activity and the risks involved are very effective in choosing gloves. It should be noted that wearing any type of safety gloves may not be suitable for any kind of work, as it can have unpleasant consequences. Each glove is designed and manufactured for a specific activity that is capable of protecting the hands and fingers in the same range of work. Gloves are used in many industrial applications to protect the hands against dangers such as mechanical damages or thermal, radiation, biological, chemical, electrical, vibration, spark, and flame hazards [1].

C.3. Duration of Work

Most gloves are used for a long time by workers, engineers, etc. Therefore, the length of time periods of using gloves is very important. Long-time usage can change the effect of gloves and affect the performance, strength, comfort, and working skill of the wearer. The tests used to evaluate gloves are usually either sudden or short-term and performed only once. For all these reasons, these tests cannot measure the long-term effects of wearing gloves. In other words, assessing the effect of wearing gloves on hand performance with single-use tests and without considering time periods may have illusory results [13].

C.4. Type of Contact

Contact with objects and hazardous materials may occur by accidental or intentional contact. When the hand is not directly exposed to hazardous materials and for instance, it is exposed to discharge or leakage of materials, an accidental contact occurs. The intentional contact relates to tasks in which exposure to dangerous substances is inevitable. For example, immersing hands in liquids, directly handling an object, and treating materials that are coated or saturated with hazardous substances and direct handling of alive tissues are categorized as intentional contact. In accidental chemical contact, disposable gloves can be used but in intentional and long-term contact, in order to prevent attack and penetration of materials inside the gloves, re-useable gloves should be employed [1].

To select the appropriate glove for the desired activity, familiarity with the safety signs and warnings on them is necessary. In addition, the presence of a safety mark on the glove indicates that gloves can provide the minimum requirements for a specific purpose. It should be noted that the performance of protective gloves is significantly affected by burnout and durability. For instance, the level of performance after one year of the production of gloves is normally reduced even before it is used [25]. Therefore, the expiration date should be indicated on gloves and packaging. Since for every kind of protection, usually materials with a different protective level are provided, and along with the safety symbols, their functional level should also be specified [25].

III. SAFETY GLOVES INFORMATION

Protective gloves are usually prepared to protect the palm,

TABLE I
SELECTING GLOVES FOR PROTECTION AGAINST VARIOUS INJURIES [27-29]

Type of gloves and application	Materials and design
Aircrew gloves; these gloves are for keeping the crew's hands warm during the flight and must be flame retardant, water resistant and improve the ability to grasp and control objects and devices.	The materials used in the palms and fingers are leather and fire-resistant fabric.
Anti-vibration gloves; that are used to protect workers' hands when using vibrating tools such as drills and jackhammers, and It should have good resistance to puncture.	Largely composed of leather, polyester, nylon, polymer, spandex, or cotton. The glove palm may contain vibration control pads such as leather, foam or rubber.
Antistatic gloves; used to work with delicate components and destroy the electrostatic properties	Nitrile, nylon, and carbon fibers are the most common. Acrylic fibers or a polyurethane coating may be used.
Chainmail gloves; they have excellent protection against puncture and cutting. They are commonly used in food preparation and knife work.	Made of metal chains attached to leather or cotton fabric.
Tactical gloves; for use by the police and military to increase grip strength and range of fingers movement.	Made of leather, nylon, neoprene, spandex, Amara, Lycra, Kevlar, Nomex, and Spandura. Linings may include foam, microfleece, polyester, Thinsulate, Kevlar, or Nomex.
Chemical gloves; which are suitable for use in laboratory environments and chemical manipulations and should protect the hands against chemicals and abrasion. It has different thickness levels and may be disposable or reusable.	Composed of nitrile, neoprene, latex, vinyl, rubber or Viton, and other materials.
Electrical gloves; prevent electric shock, electric arc and explosion when working with voltage.	All of the electric gloves are made of natural rubber but may be included leather in the structure for comfort and resistance to tearing.
Firefighter gloves; have high strength and are flame resistant, heat resistant, waterproof, puncture and tear resistant and suitable for firefighting operations.	There are combinations of leather that can be covered with cotton or Nomex. Sometimes these gloves are double-layered, in which case they are made of aluminum or Kevlar.
Flame retardant gloves; that provide excellent protection against industrial processes. These are usually less durable than fireproof gloves and are more resistant to industrial work.	Leather, carbon fiber, Nomex, and Goretex are common materials. Gloves may be lined with fleece or cotton.
Cryogenic gloves; protect human hands and arms in very cold environments (liquid nitrogen, etc.). They offer good water resistance and flexibility.	Often made of nylon Taslan, PTFE, and silicone.
Garden gloves; are general, multipurpose gloves for landscaping, and terrain repair. They oppose abrasion while enhancing grip.	Leather, canvas, jersey, knit, cotton, latex, plastic, rubber, and vinyl.
Driving gloves; are used for better grip and control and driving gloves. They usually have an exposed knuckle and opisthenar for added flexibility.	Made entirely of leather
Medical gloves; are usually disposable and are used as a barrier between caregivers and patients.	Most prominently latex, but also nitrile, rubber, vinyl, and neoprene. Powdered cornstarch is sometimes used to keep gloves pliable.
Mechanics gloves; are made for use by machine repair workers. Abrasion resistance, air permeability and oil penetration resistance and flexibility are important parameters in these gloves.	Materials are not limited and various materials such as leather/suede, polyester, nylon, spandex, cotton, rubber, PVC, neoprene and Kevlar, along with foam, gel, and TPR padding.

fingers and wrist. Occupational hazards and environmental, recreational and aviation hazards are among the items, in which it is necessary to wear gloves in order to protect hands. Each glove is usually designed for specific end-uses, but may be suitable for other purposes as well. Therefore, it is important to assess the risks before selecting a suitable glove [26]. Since the design of gloves and the materials used in their preparation determine the application of each glove, Table I lists the most common protective gloves and materials and their applications.

IV. INTRODUCTION OF HAND PARTS AND THEIR PERFORMANCE

Since the current paper discusses the properties of protective gloves and also the hand protection against dangers, hence, the definition of damage and the various types of injuries have been presented. Moreover, various parts of the hands and their muscles and bones that are effective in their movement are introduced. In addition, a brief acknowledgment of their tasks has been carried out.

In medical science, any strike or injury to the body that has been imposed from the outside and the internal factors are not the cause of harm is a trauma [30]. In other words, trauma is any damage caused by increased input energy to the body and this energy may be shocks in the form of mechanical, thermal, chemical, nuclear or others. Damage to the body may occur as a result of the execution of any kind of external force. Considering that this damage is related to the soft tissue (muscle, skin, blood vessels, and nerves) or the skeletal tissue of the human body and its joints, it is divided into musculoskeletal or wound trauma. Muscle injuries result from the onset of force on the part of the body and it is an unwanted force that is injected through the body. Besides, a variety of skeletal injuries include fractures, luxation, torsion, cramps, and muscle spasm. The second type of injury is the wound, which is any kind of cleft or loss of connective tissue in the body, both inside and outside the body. The wounds are divided into two groups of open and closed wounds. Various types of open wounds consisted of slit wounds or cured sores, ripped wounds, scars, xystos and perforated wounds such as a gunshot. The common types of closed wounds can be described as bruises or crushing [31].

The human hand is a highly complex and multifaceted organ and is the last member of the mechanical leverage chain that begins at the shoulder [32]. The mobility of the shoulders, elbows, and wrists occurs on different planes and allows the hand to move in large volumes of space. Therefore, the hand is significantly movable and can change its figure to match the shape of objects, in order to move or touch them. In addition, the movement and mobility of 19 bones and 14 joints of the hand provide excellent hand function. The wrist is a set, consisting of eight parts of the bone. The soft tissues and structures around the bones are exposed to tendons that cross the joints and connect them.

The fingers and thumb are the basic parts of the hand. Each finger unit consists of metacarpal and three phalanges

Fig. 1. Important bones in the mobility of the hand.

(two in the thumb) and joins to the middle of the hand. The fingers were named from the radial bone to ulnar which are called: 1) Thumb, 2) Index finger, 3) Middle finger, 4) Ring finger, and 5) Little finger, respectively. There are proximal joints (PIP) and distal joints (DTP) between the phalanges of the fingers that connect the two phalanges together, but the thumb has only one inter-phalangeal (IP) joint. The thenar area at the palmar side is formed by thumb muscles and another promontory hypothenar is located in the opposite direction. The third prominent part of the hand is the palmar, where it extends from the little finger to the index finger, similar to the pad. Fig. 1 shows the different parts of the hand.

The wrist set is surrounded by 10 tendons that are located at the edge of the bones. Three flexors and three extensors control the arched or crescent movement and the radial (abduction) and ulnar (adduction) deviation of the wrist. They also support the movement of flexion and extension of the wrist. The wrist has complex movements including the flexion/extension, radial/ulnar deviation, and the axial rotation of the supination/pronation; it is also possible to combine these movements. The types of wrist motion are shown in Fig. 2.

The wrist movement range for various complex actions are as follows: flexion 65°-80°, extension 55°-75°, radial deviation 25°-65° and the ulnar 30°-45° which vary depending on the individual ability.

The ranges of finger activities for four fingers and thumbs are described individually [33]. The joints in each of the four fingers allow the three axial movements of the fingers. Therefore, the fingers can perform flexion and extension; adduction and abduction; radial and ulnar. The flexion range of the fingers is from zero to almost 90°, but

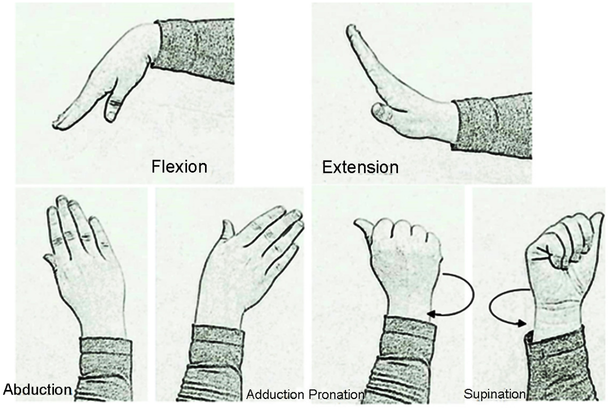
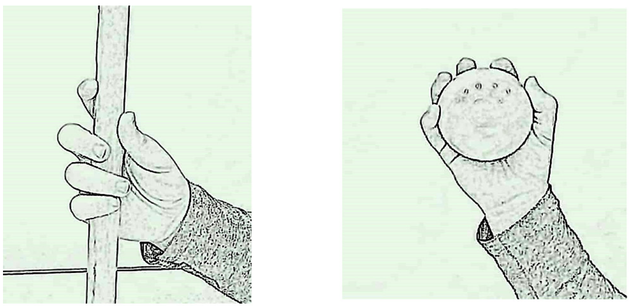


Fig. 2. Types of wrist movements.

this value varies among different fingers. The fifth finger has the most flexibility of about 95° and the second finger or the index finger's flexibility is 70°, approximately [33].

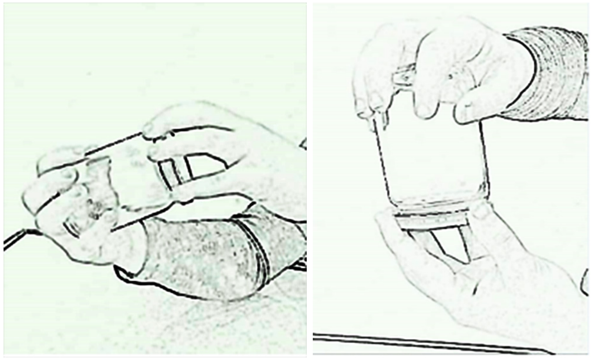
Opposition movement is the most important function of the thumb movement, in which the tip of the thumb moves towards the tip of the little finger [34]. In this movement, there is a change in the angle of thumb with the rotation from a normal position. The thumb flexion range varies considerably between different people, but the extension range of the thumb can be altered from zero position to 15°.

Many attempts were made to classify different patterns of hand performance. Hand function for most tasks can be categorized as grip (grasp), pinch, touch and manual dexterity. The grip performance can be divided into two distinct models; the power grip and the precision maneuver (taking the object along one axis). It is important that the basic needs of the operations with objects in both situations must be respected. Grasping or gripping is a powerful action that utilizes all the three-finger joints, so that the object is held between the finger and the palm, and by using the thumb to the palm, the object is safely placed in the palm of hand. In precision maneuver, the object positioned between the flexor of the fingers and the thumb and is pressed slightly. One of the important distinctions between the power grip and precision maneuver is the difference in the position of



(a) (b)

Fig. 3. Two fundamental patterns of hand function: (a) power grip and (b) precision maneuver.



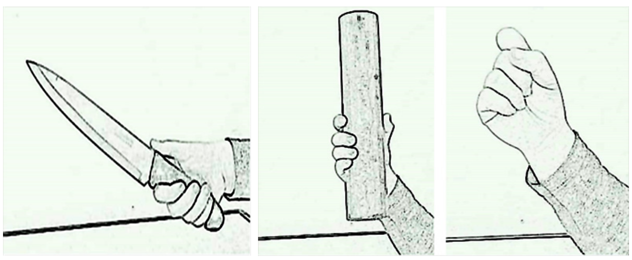
(a) (b)

Fig. 4. Unscrewing the lid of a tightly closed jar: (a) as the motion is begun and (b) as the lid loosens.

the wrist, such that they are carefully taken into practice to increase the touch of the fingers. In the precision maneuver, fingers have been drawn to increase the range of the touch. Another important difference between the power grip and precision maneuver is the fundamental difference between the thumb positions in each of the modes. In the power grip, the thumb is pulled in, but in the precision maneuver, the palm is pulled outward. The association between hand and forearm is also significant in these two tasks. In the power grip, the hand always diverges towards the ulnar and the wrist stays in a neutral state, so that the thumb axis is aligned with the arm; however, in the precision maneuver, the axis of the thumb is aligned with the object (Fig. 3) [34].

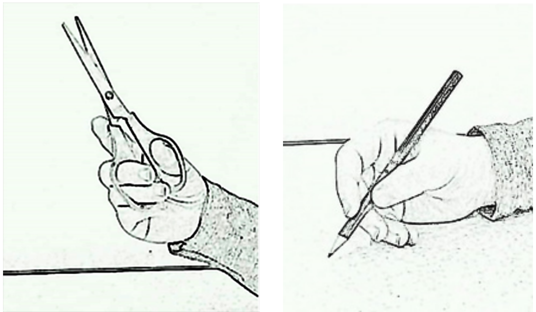
Daily tasks that are performed by hands often include both power grip and precision maneuver [34]. Moreover, a few examples of activities consist of a combination of different tasks. It is possible to point out the unlocking of the lid of a tightly closed jar which performs grip and torque action, simultaneously (Fig. 4).

For a different kind of power grip, one can hold objects and apply force with precision and strength [34]. In other words, this task is an element of power in which the element of accuracy also plays an important role (Fig. 5). The dynamic tripod is a kind of precise movement in which the thumb, index, and middle finger work together (such as scissors) to control the object, accurately;



(a) (b) (c)

Fig. 5. (a) The fencing grip, (b) the coal-hammer grip, and (c) bunched fist.



(a) (b)

Fig. 6. Dynamic tripod: (a) use of scissors and (b) a pencil.

while the ring and little fingers are doing the task of supporting and controlling (Fig. 6).

Pinch is referred to as the tiny touch of small objects. Pinch types can be categorized as two-point pinch (the object pinch between the thumb and index finger) (Fig. 7) and a three-point pinch (the object pinch between the thumb, index and middle finger and the middle pinch) (Fig. 8). The types of pinching are classified according to the finger phalanges that are used in activity on the object [34].

Torque is another strength capability of the hand. The difference in the grip of the handles and also considering the muscles which are involved during the operation has led to the classification of torque into different types [10]. The most common torque tasks, are: using wrist twist to turn a handle (as with a screwdriver), using wrist flexion to turn a handle (as with a motorbike throttle), using lateral force along a handle to turn it around a central axis (as with a car steering wheel), using pushing/pulling at right angles to a handle to turn it around a central axis (as on a wrench), and twisting a screw cap off a bottle (using finger pinch) [10].

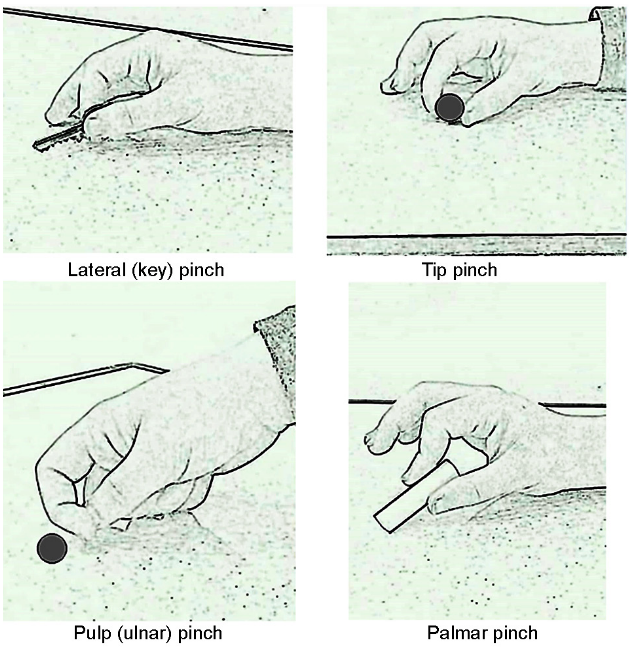


Fig. 7. Types of two-point pinch.

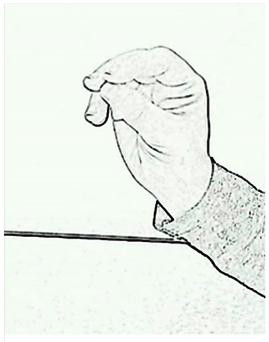


Fig. 8. Three-point pinch.

V. EFFECT OF PROTECTIVE GLOVES ON HAND PERFORMANCE

Effective factors in the selection of protective gloves and their design parameters that were previously stated (section III and IV) both affect the hand performance after wearing gloves. Therefore, various hand functions after wearing gloves should be evaluated. In order to provide the ability for hand to perform different activities, it should have both sensory and motor abilities. Motor functions include strength capabilities, range of motion, manual dexterity and muscle activity. In addition, the sensitivity and comfort of hand should be considered when wearing gloves. Hand functions can be classified into two dynamic and static, or one-dimensional and multi-dimensional groups. For example, the manual dexterity is a multidimensional test, because it influences strength, sensory function, comfort, range of motion, and many other factors. But because other performance capabilities do not affect the tactile sensitivity of the hand and finger, sensitivity is a one-dimensional function [10].

A. Strength Capabilities of the Hand

Muscle strength is one of the hand abilities in operating, which is generally referred to as grip and grasp, all kinds of pinches and forearm torque [10]. The muscle strength can be applied dynamically and statically, so the measurement of power is done both in a dynamic and static manner. When the hand enters the maximum compressive force, tensile strength or torsion torque, static strength occurs. While measuring dynamic power is more complicated than static power. When applying dynamic muscular force, the length of the muscles changes significantly, which is why the force applied when moving the body is known as dynamic power [10].

Various types of tools that have been reported in studies including the types of dynamometers [35] (i.e. the Jamar dynamometer, Rolyan dynamometer, dynamometer made by MIE Medical Research Ltd.), pinch gauges (B&L Pinch Gauge and Preston Pinch Gauge), or torque sensors (load cells, strain gauges, and torque sensors), are used to measure the hand power [35]. The strength capabilities of the hand, due to factors such as manual dexterity and range of motion are multidimensional tests. To evaluate and test the strength of the hand, the conditions of the test must be similar to the actual working conditions [35].

Many studies have examined various factors affecting hand strength after wearing gloves. Numerous studies have shown the negative impact of utilizing glove on hand power performance [36-45] while increased grip strength after using gloves has been reported in several studies [45].

Different test conditions, including climate, diameter and length of the dynamometer handle, hand and wrist position when applying force, the type of work required in the test process, and many other factors may be the cause of these conflicting results [46-48]. A number of studies have examined the effect of thickness, the number of layers and design of gloves on hand strength performance [49,50] and presented that increasing thickness has a negative effect on hand strength performance [23,49-54], but some studies also reported an increase in grip and pinch strength due to increased glove thickness [55,56].

The type of gloves and the physical and mechanical properties of the materials [59] used in the preparation of the gloves and their influence on the application of power by hand have also been considered by researchers. These factors affect the final force applied by the hand due to the impact on the friction [60-62] of the glove with objects, the stiffness of the glove and the feeling of fatigue of the hand. Application of gloves with proper size [59], force exertion by the dominant or non-dominant hand, the gender [63] and many other factors affect the force applied by the hand. The hand torque after wearing gloves was also tested by researchers [64-68] which found conflicting results in studies. Several studies have shown a positive effect of gloves on torque performance; however, some of them stated a number of negative effect or ineffective use of gloves on torque performance.

Research on the pinch performance was much less than that of the grip, but studies have revealed that gloves can reduce the performance of the pinch, but in some cases, researchers have reported an increase in the pinch strength due to the use of gloves [69-72]. Therefore, in general, the effect of using gloves on the power of pinch and torque is not very clear and requires further research.

B. Muscle Activity and Fatigue

The continuity of work and longtime activity can lead to symptoms that are sometimes painful and uncomfortable. In fact, fatigue is an unpleasant state that causes exhaustion in the muscles due to long period activities or applying vibratory and rhythmic powers. Environmental factors such as heat, cold or humidity, gloves design parameters such as flexural strength, material, comfort and many other effective factors can influence the severity of fatigue [10].

Fatigue may occur in static or dynamic operations. In static activities, a group of muscles are involved in a steady state and if the muscle is impacted by force during a long time, it is contracted without any movement. In dynamic activities, muscle movement, contraction and expansion accelerate the blood flow, consequently; less fatigue is observed in these activities than in static activities. One of the methods to measure muscle activity is using the electromyography device. In this method, muscle contractions can be perceived using electrodes that are mounted on the muscles. In this technique of the measurement, stronger contractions cause larger signals that result in fast muscle tiredness [10].

Summaries of previous studies on muscle activity and fatigue display that using gloves increases the activity of various muscles in the hand, resulting in earlier fatigue. But the efficiency of hand function is affected by factors such as the appropriate size of gloves, friction of gloves with objects, material, physical and mechanical properties of gloves. It should be noted that the position of the hand when doing work is also effective in fatigue [54,68,73-76].

C. Manual Dexterity

Manual dexterity is another skill in which nerves, muscles, joints and ligaments are involved [10]. The main aspects of manual dexterity are influenced by factors such as the range of motion of the fingers and wrists, the sensitivity and coordination of the hands. Therefore, this skill of the hand can be considered as a multidimensional performance. Manual dexterity has been measured by a number of standard tests such as the Bennett hand tool dexterity test, Minnesota rate of manipulation-turning or pegboard test [77], O'Connor dexterity test, Pennsylvania bimanual work sample assembly test, rope knotting test, block manipulation and nut and bolt test (the basis of most manual dexterity tests is to pick up and move objects and put each object in the right place) [78]. Due to the fact that the purpose is to measure one or two-finger dexterity or whole hand dexterity, the appropriate test should be selected.

But, despite all these common tests of dexterity testing, it is desirable to design a test to assess the performance of each glove by considering the work that is expected from the glove wearer. Therefore, when more factors such

TABLE II
STUDIES RELATED TO THE EFFECTS OF GLOVES ON STRENGTH, MANUAL DEXTERITY AND RANGE OF MOTION

Research	Method and tool	Hand condition	Influencing factor	Dependent variable	Result
Bradley (1969) [79]	Five types of control (push buttons, toggle switches, knobs, horizontally operable levers, and arid vertically operable levers)	Bare hand, wool glove, double glove, i.e., leather glove over wool glove	Type of glove, physical characteristics of the control, and type of control operation required	Control operation time	Wearing gloves has a negative effect on operation control
Taylor and Berman (1982) [85]	Pressing the keyboard	Bare hands, neoprene inner, cape leather flying, in conjunction with the inner glove	Hand conditions	Sensory feedback on keying	No significant differences between glove conditions
Plummer *et al.* (1985) [86]	Bennett hand tool dexterity test	Three single gloves and six double gloves combinations plus the bare hand condition	Hand conditions	Manual dexterity	Reduces manual dexterity after wearing double gloves compared to single gloves
Riley *et al.* (1985) [8]	Tension meter	No glove, one glove, and two gloves	Hand conditions	Maximum pull force, maximum push force, maximum wrist flexion torque, and maximum wrist extension torque	One-glove condition was superior to the conditions of no glove or double gloves for the forces and torques measured
Johnson and Sleeper (1986) [80]	O'connor and pegboard test	Bare-handed, chemical protective hand-wear, and headgear	Hand-wear and headgear	Manual dexterity	After wearing gloves manual dexterity is greatly reduced
Karis (1987) [92]	Control an airplane controller	No gloves, flight gloves, and a combination of three gloves worn simultaneously	Hand condition	Skill on motor control	Increased skill in controlling after wearing gloves due to increased friction
Chen *et al.* (1989) [59]	Cylindrical handle, electromyography	Bare handed and letters stand for leather, cotton, and rough deerskin	Glove size and glove material	Maximum torque exertion and small parts assembly	For the maximum exertion task, the size of the gloves does not affect the task, but the material is effective and for the assembly task size and the materials have a combined effect
Bellingar and Slocum (1993) [83]	Two tasks typical of pesticide applicators, two Locam cameras	Gloved and ungloved	Hand conditions	Hand movement	Kinematic motion of the hand appeared to decrease while wearing protective gloves
Bensel (1993) [87]	Minnesota, O'Connor, Cord and cylinder, Bennett hand-tool dexterity, and Rifle disassembly/assembly	Bare hand, three thicknesses of chemical protective gloves, 0.18, 0.36, and 0.64 mm	Gloves thickness	Manual dexterity	Manual dexterity is reduced by increasing the thickness of the glove

Research	Method and tool	Hand condition	Influencing factor	Dependent variable	Result
Nelson and Mital (1995) [52]	Texture identification test, two-point discrimination test, using scissors to cut out three different geometric shapes	Bare handed, Latex gloves of five different thicknesses 0.21, 0.51, 0.65, 0.76, and 0·83 mm)	Dexterity, tactility, grip strength and wrist flexibility, and penetration force	Thickness of the latex gloves	1. Increasing thickness has a negative effect on grip and sensitivity 2. Thickness had no significant effect on dexterity 3. Hand protection improved with thickening
Moore *et al.* (1995) [49]	Hand dynamometer, B&L pinch gauge	(1) Bare hand, (2) hand with a normal sized latex examination glove, and (3) hand with a tight fitting latex examination glove	Hand condition	Power grip strength, pinch strength, and manual dexterity	Latex gloves do not have an effect on strength, but inappropriate size reduces the manual dexterity
Bronkema and Bishu (1996) [61]	Standard hand dynamometer	Cotton, leather, and bare hand	Glove type, friction level, load lifted, trial, and gender	Grasping force and grasping control	Friction and load both affect the grasp force
Phillips *et al.* (1997) [23]	Texture matching, Point discrimination,Stereognosis with 2-D visual cue, Stereognosis without visual cue, Motor function-grip	No gloves, single latex glove, two pairs of latex gloves, latex-Repel-Lite®-latex, and latex-Lifeliner®-latex	Hand conditions	Grip strength, dexterity, and tactility	Thicker gloves reduce sensitivity and skill but do not have a multivariate impact on the motor tasks
Lowe and Freivalds (1996) [93]		Spectra, nitrile, and conventional thick cotton glove	Glove types, pinch forces shelf height, and handling strategies	Windshield glass handling	Gloves with higher thickness provide better performance
Tsaousidis and Freivalds (1998) [70]	A handle and two parallel metal bars was connected to a pressure transducer	A leather glove without lining and bare hand	Hand conditions	Pinch, wrist flexion, and grip force	No significant effect of gloves on pinch and torque and significant effect of gloves on grip strength
Chen *et al.* (1998) [82]	Monofilament test, O'Connor dexterity test, scissor cutting time, vibration test count, corneometer measure, borg's CR-10 scale measure, Grumman scale, and weight measurement	4 gloves with latex, latex with liners A, B, and C layers	4 gloves, two temperatures, and gender	Tactility and dexterity	The effect of gloves was significant but the temperature and gender were not significant
Muralidhar *et al.* (1999) [2]	Pegboard task, block manipulation, rope knotting, assembly task, grip strength with Jamar dynamometer, and algometer test	Bare hand, single glove, double glove, contour glove, and laminar glove	Hand conditions (different gloves design)	Grip force, dexterity, Pressure protection	Gloves decrease grip force, and hand dexterity but increases protection
Sawyer and Bennett (2006) [88]	Purdue pegboard test	Latex and nitrile safe skin gloves	Hand conditions and size	Hand and finger dexterity	The latex gloves provide better skill with greater thickness, but this difference was not very significant
Krausman and Nussbaum (2007) [89]	Wearable mouse and touch pad to enter text	Barehanded, gloves with thickness of 7, 14, and 25 mm	Glove thickness and mask use	Performance in entering text	1. Suggesting that thin protective gloves are more suitable than thicker gloves 2. Mask use did not affect task performance

Research	Method and tool	Hand condition	Influencing factor	Dependent variable	Result
Gnaneswaran *et al.* (2008) [91]	Jamar hand dynamometer, and pegboard test	Bare hand, latex with powder, latex without powder, vinyl with powder, and vinyl without powder	Hand condition, powdered and non-powdered	Grip and pinch strengths, dexterity, tactility, and manipulability	The latex gloves with powder are recommended over vinyl gloves but if a person (health care provider or receiver) is sensitized to latex allergen, then the use of vinyl gloves is suggested
Berger *et al.* (2009) [84]	O'Connor and purdue pegboard test	Nitrile Semper care and nitrile safe skin	Hand condition and dry and wet conditions	Finger dexterity	Reduced both gloves finger dexterity
Yalamarty *et al.* (2009) [48]	Grip dynamometer, (Takei company), pinch gauge (baseline), complete connection of electric power lines in the field	Bare-hand, electric utility lineman gloves	Hand conditions, four trials per task, and two-arm positions	Hand grip strength, pinch grip strength, an assembly task, and a rope knotting task	Decrease in grip strength and the time required to complete tasks due to wear glove
Drabek *et al.* [90] (2010)	Grooved pegboard test	Bare-handed, right size, too large, and too small	Size of gloves, the effect of time and fatigue	Manual dexterity	Wearing wrong size of gloves reduces the performance relative to bare hands and right size gloves
Dianat *et al.* (2010) [72]	Screw-driving task (MT8-3 biological telemetry system (MIE Medical Research Ltd., Leeds,UK), pegboard test, monofilament test, pinch gauge (B&L Engineering, Tustin, CA, USA), torque meter and a T-shaped handle	Cotton, nylon or nitrile gloves as well as barehanded	Hand conditions, shorter and longer duration effects of protective gloves, and hand conditions	Hand performance capabilities (muscle activity, dexterity, touch sensitivity, finger pinch, and forearm torque strength) and subjective assessments of discomfort and ease of manipulation	Wearing gloves significantly increased the muscle activity, pinch strength and discomfort but reduced the dexterity and touch sensitivity
Wells *et al.* (2010) [56]	Electromyographic (EMG) and hand grip dynamometer	Bare hand and five classes of gloves; 0, 1, 2, 3, and 4	Thickness and size	Electrical activity (EMG), performance times and ratings of comfort, fit and dexterity, and grip strength	Glove thickness increased: Performance decreased, effort and EMG amplitude increased and self-rated comfort, fit, and overall rating decreased
Dianat *et al.* (2012) [95]	Industrial assembly tasks involving pliers	Bare hand, cotton, nylon, and nitrile gloves	Hand conditions and duration of the task	Muscle activity, wrist posture, touch sensitivity, hand grip, and forearm torque strength	Gloves tend to increase muscle activity, wrist posture and discomfort and to decrease touch sensitivity, hand grip, and forearm torque strength
Yu *et al.* (2019) [44]	Calibrated metal goniometer, Jamar hand dynamometer, semmes–Weinstein monofilament test, purdue pegboard, and marble transport test	War-gaming glove and hiking glove	Fit of glove, physical and mechanical properties of glove materials, and type of gloves	Ranges of motion, grip strength, finger tactile sensitivity, finger dexterity, ability in holding and handling, and comfort	Active range of motion of fingers, finger tactile sensitivity, gripping strength and ability to handle pegs and marbles decreased with the use of gloves compared with bare hands

as the movement of the fingers together, movement of both hands together and movement of the eye and hand together are involved, the results will be closer to reality. Thus, multidimensional tests such as manual dexterity, strength capability or muscle activity may affect the choice of gloves and effective parameters on the design of gloves (explained in the previous sections), in addition to hand function characteristics.

Summarizing the results of published studies on the effect of gloves on manual dexterity performance presents that using gloves increases the working duration or the number of errors; thus, reduces hand dexterity [2,39,48,72,79-85]. Manual dexterity can be affected by the glove thickness and mostly reduces by increasing the thickness [23,52,56,86-89]. Also, using the right size of gloves can affect manual dexterity [49,90], because if the glove is too loose, it is weighty and it gets stuck around and becomes annoying. On the other hand, if the glove is too tight, the comfort is affected that leads to the reduction of manual dexterity. The materials used in the preparation of gloves are an important factor in the manual dexterity; harder and bulkier materials can negatively affect the manual dexterity [59,91]. Mutually, various studies have shown that thin gloves such as latex gloves have little effect on manual dexterity performance. However, improved hand skills after wearing gloves have been reported by increasing the friction between gloves and objects [61,92,93].

D. Range of Motion

The hands and fingers joints allow them to bend and move in different directions. The wrists and each of the fingers have their movements; however, the amount of their movement is different (Section II). Wearing gloves may change the movement of these joints and limit the movements. Limitation of hands and fingers movement reduces people's performance and increases muscle activity and also fatigue. The environmental conditions, the duration of the work cycle, the size of the glove and many other factors mentioned in Section III may also affect the movement angle. Hand-gauge measurement is performed using various tools such as manual and electrical goniometers and video cameras [17]. Few studies have been conducted on the effect of wearing gloves on the range of motion, but studies have reported that wearing gloves reduces the range of motion of fingers and wrist [8,39,44,83].

In order to overlook on the previous researches regarding the manual dexterity and range of motion, the details of the papers are gathered in Table II.

E. Tactile Sensitivity

The textures and grooves on the human hand make sensory and tactile sensations in palms and fingers. The tactile sensitivity is a feature that enables the hands and fingers to understand the shape, softness and roughness, material, size, and the texture of the objects. In other words, sensitivity to touch is perceived by the ability to recognize each of these features by the skin receptor on the hand. It is noteworthy that in addition to understanding all the touch elements such as material, shape and size, the time of understanding these features also affects the sensitivity of the hand. Usually, after wearing gloves, the sensitivity and perception of hands and fingers decrease due to the extra layers between the hands and fingers. Fess (1995) categorized the touch sensitivity test into three distinct groups consisted of: 1) Detection of the distance between two points, 2) Assessing the threshold of touch, and 3) Examining objects, shapes and textures. According to this category, each of these capabilities has been designed and built. Because of the pressure variation, size and diameter of the filaments, the monofilament test was a proper and accurate test for assessing the threshold of the touch, which presented a more logical and realistic evaluation. A two-point discrimination test is also used to recognize the distance between two points and another method for assessing the sensitivity is the shape-texture identification test. Despite all of these tests, the problem of time brings a large gap in the assessment of the sensitivity of the touch, which may result in mistakes. How long the pressure lasts, how it lasts and how long it takes to feel it are also important in sensitivity results that have not been taken into account so far. Another thing that has been overlooked until now is the ability to understand the roughness, softness, material, temperature, humidity and other factors changing by wearing gloves. Of course, in some cases, the purpose of wearing gloves is to reduce some sensory abilities, for example, when dealing with harsh or sharp objects or in contact with hot objects, the reduction of touch capacity is not a disadvantage of gloves [10].

Generally, several studies have shown that wearing gloves can affect the hand tactile sensitivity in a negative way, but some studies have reported that the use of gloves has no significant impact on hand sensitivity [13,39,44,45,56,72,81,95-97]. There are two possible reasons for this contradiction in results: one is the change in the characteristics of the tested gloves, and the other is the diversity of the type of tactile sensitivity test. Moreover, the gloves' characteristics, such as the thickness, flexibility, and stiffness of the gloves, are influential on the hand tactile sensitivity [23,98].

VI. CONCLUSION

Today, the importance of hand and body protection is more acknowledged than ever before, and for this reason, many studies have been conducted in this field. In this regard, products such as highly functional clothing with physiological comfort are produced and the use of methods such as nanotechnology, biotechnology, electrical technology in the field of manufacturing new protective equipment have been investigated [1]. From the past until now, new types of protective gloves such as anti-abrasive glove [99], anti-slip glove [100], multilayered glove [101], and double face glove [102], welding glove [103], cut resistant glove [104], utility glove [105], etc., have been produced and marketed. Also, new methods and materials for producing better and more suitable protective gloves are being proposed, continuously. This review paper includes the literature on protective gloves and its impact on various aspects of hand performance. As a result of previous studies, it was revealed that wearing gloves in most cases reduces hand dexterity, sensitivity, strength as well as increased discomfort, muscle activity and fatigue. However, there are contradictory results which could be due to the weakness in the methods of assessing the capabilities of gloves and lack of consideration of the actual condition of the gloves usage. The differences are due to the varieties in the experimental conditions, types of gloves, how the measurements were done, etc. In this case, the solution would be to develop or use standard test methods that provide an accurate estimation. Up to now, few studies have examined the design of gloves and how to improve each hand function by using design changes. According to the studies reviewed in this paper, it seems that there still exist some points that are necessary to be considered in the field of studying protective gloves including the use of gloves in long periods and real working conditions. Moreover, assessment of different features of hand performance with regards to the glove construction, and also the effect of glove's components physical and mechanical characteristics on the operative protection capabilities of gloves, are prominent aspects that are essential to be considered as the subjects of future researches on protective gloves.

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REVIEW PAPER

Multi-dimensional Analytical Base Method for Evaluating Camouflage Patterns

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Abstract- **Precise evaluation of camouflage patterns is very important to achieve an effective protective cover. Recently, researchers have focused on proposing computational methods for camouflage evaluation using algorithms of image feature extraction. Although the available indexes determine the similarity of camouflage patterns to the environmental background, they generally suffer from a lack of quantified camouflage principles. The main idea of this paper is to propose a new evaluation metric by defining seven camouflage factors to evaluate camouflage patterns. To this end, several conceptual factors of camouflage that are vital for a camouflage pattern were defined. Accordingly, if a pattern does not contain the mentioned camouflage factors, it cannot be considered as an effective protective pattern. In this regard, if a pattern comprises more of the camouflage factors, it has better efficiency in concealment. To indicate the performance of the proposed metric, we analyzed the effectiveness of different customary camouflage patterns using the fundamental factors to categorize them into three different classes including inefficient, moderately efficient, and efficient. The results showed that the camouflage evaluation with the proposed camouflage features is reliable and reasonable.**

Keywords: **military uniform, camouflage factors, evaluation metric, quantitative method**

I. INTRODUCTION

Military uniforms are an unavoidable part of national authority and identity. Today, military uniforms have a camouflage effect to safeguard the army forces in battles. Although the early military uniforms had no camouflage pattern, the recently produced uniforms contain camouflage patterns due to the development of military tactics [1]. Therefore, the military forces attempt to produce more successful camouflage patterns concerning the strategic regions. In this regard, the evaluation of camouflage patterns is an important step to produce an effective camouflage pattern [2]. Researchers proposed different quantitative metrics based on image feature extraction to evaluate camouflage patterns [2-8].

Indeed, all the available evaluation methods of camouflage patterns are computable approaches based on the feature similarity between the camouflage pattern and its background image. For example, some researchers exploited the algorithms of image quality assessment to evaluate the effectiveness of a camouflage pattern for a background image [3,6,8,9]. Liming and Weidong proposed weight structural similarity (WSSIM) index based on the human visual model to calculate the similarity between a camouflage pattern and a background image. They also calculated several image features (e.g. mean of luminance, image entropy, and correlation length) between the camouflage pattern and the background image to understand what features of a camouflage pattern have the maximum effect on human detection performance [3]. Lin *et al.* proposed a camouflage similarity index by averaging the color differences between the pixels of the camouflage pattern and its background to assess the performance of camouflage patterns. The results showed that their proposed metric correlated well with the performance of human detection variables [8]. Lin *et al.* investigated the efficiency of the universal image quality index (UIQI) for evaluating the camouflage patterns and

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revealed that the UIQI (a special case of SSIM index) correlated well with the human detection performance and it could be a potential camouflage assessment tool [6]. Xue *et al.* proposed the nonlinear fusion of several image features to quantitatively assess the degree to which the camouflage pattern and background differ in relation to background-related and internal features. They demonstrated that the proposed framework is an effective method for evaluating a camouflage pattern design [7].

Since a camouflage pattern contains different features, such as background similarity, disruption, concealing, and deceiving, extracting image features for evaluating a camouflage pattern is not a comprehensive and accurate approach. In fact, existing metrics only quantitate (measure) the background similarity of a camouflage pattern while many other different factors affect the efficiency of a camouflage pattern. Therefore, all effective factors on camouflage efficiency should be considered in proposing an evaluation metric.

In this paper, we have proposed a new criterion by combining a quantitative metric and several critical camouflage factors to evaluate the camouflage efficiency of camouflage patterns. Seven fundamental principles of camouflage in nature are recognized and utilized for evaluating the common camouflage patterns. Six camouflage factors are determined qualitatively and the background similarity of camouflage patterns is calculated based on the best existing WSSIM index [3]. Therefore, we analyzed the effectiveness of different customary camouflage patterns based on these defined camouflage factors. Finally, the camouflage patterns were classified into three classes by scoring them based on the camouflage factors and the WSSIM index.

II. FUNDAMENTAL CAMOUFLAGE FACTORS

According to the camouflage principles in nature and properties of the human visual system, elementary features that are essential for a camouflage pattern can be identified. These features include element diversity in a pattern, element size, irregularity in the pattern, disruption, type of edges in the pattern, quantity of basic colors, and similarity to the background. As these features are variable, changing them in a pattern can affect the efficiency of a camouflage pattern.

A. Element Diversity in a Pattern

Cott proposed that the elements of a camouflage pattern should be various to resemble different objects of a scene, because a camouflage pattern with a single element may perceive as a single object [10].

B. Elements Size

There is not any exact information about the optimum size of camouflage pattern elements. This parameter is highly dependent on the size of the environment objects [11]. However, based on the multi-scale theory, it seems that the simultaneous existence of micro and macro elements is necessary to provide far and close distance camouflage.

C. Irregularity in the Pattern

Based on Cott's theory, the geometric relation between elements of a camouflage pattern is very important [10]. Besides, the vision system of the human is more sensitive to regularity compared with irregularity [12]. For example, the detection of a symmetric pattern is more convenient than an asymmetric pattern [13]. Therefore, the identification of an irregular pattern is more difficult than a regular pattern.

D. Disruption

Thayer proposed a disruptive coloration strategy that makes continuity between target and terrain by placing markings on the edges and near the outline of the target body [14]. A schematic illustration of disruptive comparing with distractive markings is shown in Fig. 1. As shown in Fig. 1, irregular stripes placed on the edges of the body provide the disruption feature. Moreover, the used elements should not be too small or too large to disrupt a pattern properly. In fact, the size of disruptive elements is dependent on the size of the human body and terrain objects [15,16]. Therefore, based on the human body size, the elements should have an optimum size to disrupt the camouflage pattern.

Distractive marking is a type of camouflage-making method, which delays recognition if it is used properly. This feature detracts the receiver's attention from the body outline preventing the determination of its form. Distractive marking uses conspicuous elements on the pattern and the size of elements should be small and the elements should not touch the body outline [11], whereas, in disruption, there are irregular stripes that contact the outline to break up the body outline [17]. However, it was revealed that distractive markings reduce camouflage efficiency and survival of the animal [18].

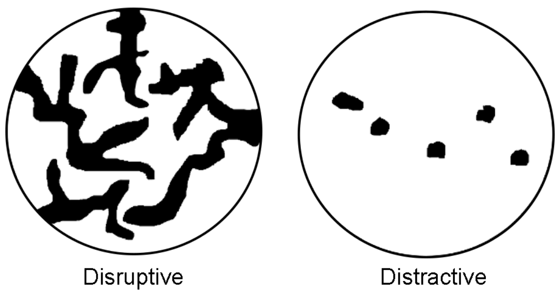


Fig. 1. Disruptive and distractive markings [17].

E. Type of Edges in the Pattern

Stevens *et al.* proposed the principle of surface disruption. According to the surface disruption theory, internal false edges in a pattern cause disruption and improve camouflage effectiveness [11]. Also, Egan *et al.* proved practically that edge enhancement promotes the effectiveness of a disruptive pattern by inducing a pictorial relief [19]. Furthermore, using color gradients for adjacent elements makes better color mixing and generates more effectiveness. Therefore, using internal false edges and color gradients simultaneously make a better camouflage effect.

F. Quantity of Basic Colors

Due to the background matching strategy, the colors of a camouflage pattern should be similar to random colors of the terrain [20]. As for color mixing at far distances [21] and camouflage in different scales, the average of the pattern colors should be equal to the average of the terrain colors. Therefore, if the pattern colors match more objects of the terrain, the camouflage efficiency is increased.

G. Similarity to Background

According to the theory of background similarity, shape, size, color and spatial distribution of a camouflage pattern should resemble the background to gain better efficiency. Since the weighted structural similarity (WSSIM) index [3] was suggested based on the human visual system and structural distortion measurement [22], the WSSIM index is an appropriate criterion to quantify the background similarity factor. Additionally, it has been proven that the SSIM index has a better correlation with subjective rating than error-based methods [22]. Also, the efficiency of the WSSIM index for evaluating the camouflage patterns has been investigated and revealed that the WSSIM index correlated well with the human detection performance [6].

III. IMPLEMENTATION

A. Collection of Camouflage Patterns and Background Images

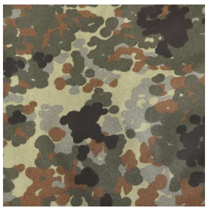
To develop the proposed metric, several famous camouflage patterns, namely Rainy, Splinter, Flecktarn, Frog-skin, Tiger-stripe, Woodland, Digital, and Multicam [23,24] were collected. The images of these camouflage patterns were downloaded [23] in JPG format with dimensions of 600×600 pixels. It must be noted that the selected patterns are common examples of designs used by the military forces. Selected camouflage patterns that are produced for woodland terrains are shown in Table I.

As for calculating the WSSIM of camouflage patterns, commonly the efficiency of a camouflage pattern is determined for specific environments, so, the appropriate images of the desired environments were captured. A Canon PowerShot G12 camera was used for capturing different images of woodland terrains in Iran. The images were used in sRGB color space with JPG format and dimension 3640×1535 pixels. The three selected background images are shown in Fig. 2. It must be noted that the exposure settings of backgrounds 1 and 2 were f/4 and 1/1250 s at ISO-200, and the settings of background 3 were f/6.3 and 1/250 s at ISO-100. In addition, all images were taken at 1:30 PM on a sunny day.

B. Evaluation of Camouflage Patterns

Based on the first six fundamental camouflage factors, i.e. element diversity, elements size, irregularity, disruption, type of edges, and colors quantity, each camouflage pattern

TABLE I
EXAMPLE CAMOUFLAGE PATTERNS OF MILITARY UNIFORMS

Pattern name	Rainy	Splinter	Flecktarn	Frog-skin
Image of pattern				
Pattern name	Tiger-stripe	Woodland	Digital	Multicam
Image of pattern				

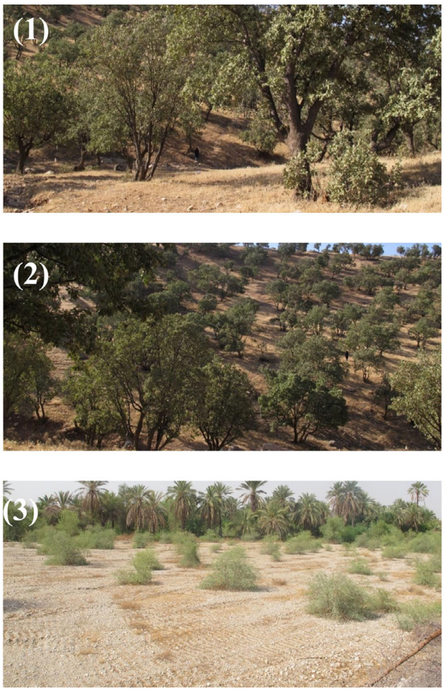


Fig. 2. Different selected background images: background (1), (2), and (3).

was analyzed to see whether it owned the defined factors. Then, to determine the seventh factor i.e. background similarity, the mean of WSSIM index for each camouflage pattern against 3 different background images was calculated. Finally, by scoring each camouflage pattern based on defined factors, they were classified into three classes including inefficient, moderately efficient, and efficient classes. The patterns were classified as inefficient if the total score was less than 5. If 4<total score<7; so the patterns are categorized as moderately efficient, and if a pattern obtains 7 factors it is classified as efficient.

B.1. Calculating WSSIM Index

Structural Similarity (SSIM) index [22] is a common index to measure the similarity between the reference and distorted signals. As for camouflage evaluation, the reference signal referred to the background image and the distorted signal is a camouflage pattern. Let x and y are the camouflage pattern and background images, respectively. The SSIM index is based on the computation of three terms, namely the luminance term, the contrast term, and the structural term which are shown in Eqs. (1) to (3), respectively [22]:

$$l(x,y)=\frac{2\mu_x\mu_y+C_1}{\mu_x^2+\mu_y^2+C_1} \quad (1)$$

$$c(x,y)=\frac{2\sigma_x\sigma_y+C_2}{\sigma_x^2+\sigma_y^2+C_2} \quad (2)$$

$$s(x,y)=\frac{2\sigma_{xy}+C_3}{\sigma_x\sigma_y+C_3} \quad (3)$$

Where, μ_x and μ_y are the mean of pixels intensity of camouflage pattern and background images, respectively. σ_x, σ_y, and σ_{xy} are the standard deviations and cross-covariance of pixels intensity for camouflage pattern and background images, respectively. As the used images are True Color images, pixel intensity refers to the intensity value in each channel, i.e. red, green, and blue channels. C_1, C_2, and C_3 are regularization constants to avoid instability for image regions where the local mean or standard deviation is close to zero.

According to Eq. (4), the overall index is a multiplicative combination of the three defined terms:

$$SSIM(x,y)=l(x,y)c(x,y)s(x,y) \quad (4)$$

The value range of SSIM is [-1, 1], and if x=y, the SSIM obtains the top value of 1 [25]. Therefore, lower SSIM means that the similarity of camouflage pattern with background image is minor. While the higher SSIM index shows more similarity of camouflage pattern with the background image. As the size of the camouflage pattern and the background image is not equal, Liming and Weidong [3] proposed Weighted-SSIM (WSSIM) index to calculate the similarity between a camouflage pattern and background image. The camouflage pattern is compared with each block of the background image with the same size to get the whole evaluation result according to Eq. (5):

$$WSSIM(x,y)=\frac{1}{M}\sum_{j=1}^{M} w_j SSIM(x_j,y_j) \quad (5)$$

Where, w_j is the weight of different blocks of background and M is the sum of the blocks. We selected w_j=1 for all of the blocks. The WSSIM was calculated for each channel R, G, and B of a camouflage pattern and background images distinctly and finally, the mean of three channels (R, G, and B) was calculated and presented as WSSIM for each pattern. To extract the RGB values from images and calculate the WSSIM index, we used Matlab Mathworks R2014a.

IV. RESULTS AND DISCUSSION

A. Quantitative Analysis of Camouflage Patterns

The SSIM index for the combination of different background images was calculated and the results are shown in Table II. If two images were identical, the SSIM gets 1, e.g. the SSIM index of background 1 with background 1 obtains 1 as seen in Table II. However, the SSIM of background 1 with background 2 obtained

TABLE II
SSIM INDEX FOR EVERY TWO BACKGROUND IMAGES

	Background 1	Background 2	Background 3
Background 1	1	0.271	0.308
Background 2	0.271	1	0.292
Background 3	0.308	0.292	1

0.271 that indicates these two background images are not exactly similar. For other backgrounds (Table II), the similarity of different backgrounds to each other is 0.308 and 0.292 that indicates the selected backgrounds were not similar. Our goal was to calculate the WSSIM of camouflage patterns for dissimilar background images. So, we can analyze the effectiveness of camouflage patterns for selected woodland images.

The WSSIM index for each camouflage pattern and three different background images are shown in Fig. 3. The average measure of WSSIM over different backgrounds shows that the MultiCam has the best performance between other patterns and the rainy pattern was the worst pattern. The MultiCam has the highest WSSIM for all backgrounds and the rainy has the lowest similarity to all backgrounds.

B. Analysis of Camouflage Patterns Based on Fundamental Camouflage Factors

The fundamental factors of camouflage for different custom camouflage patterns are shown in Table III. It was determined whether each camouflage pattern contains each defined feature or not (Table III). Detailed discussions for each pattern are presented in the following.

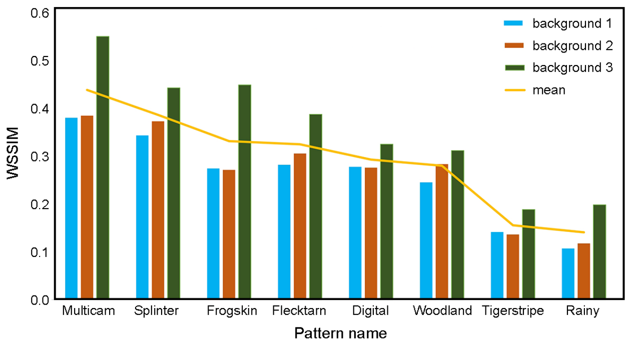


Fig. 3. WSSIM between each camouflage pattern and different backgrounds.

B.1. Rainy Pattern

The rainy pattern has a single color background with plenty of elements that resemble the falling rain. So, the rainy pattern is a single element design and does not have various elements. In terms of element size, this pattern contains micro-elements and due to the alignment of raindrops, this pattern is regular. As shown in Fig. 1, the rainy pattern does not disrupt the outline. On the other hand, the rain straits make sharp edges in the pattern, and thus they are not similar to the terrains objects. Considering Fig. 3, the WSSIM index of the rainy pattern was the minimum compared to other patterns. Some references noted that this pattern largely ineffective and rates poorly as camouflage in all environments [26]. Therefore, the rainy pattern can be rated as an inefficient pattern.

B.2. Splinter Pattern

This pattern consists of polygons that resemble splintered

TABLE III
FUNDAMENTAL FACTORS OF DIFFERENT CAMOUFLAGE PATTERNS

Pattern	Element diversity	Elements size	Irregularity	Disruption	Type of edges	Colors quantity	Background similarity (WSSIM)	Total score (out of 7)
Rainy	Single element	Micro pattern	Regular	No	Sharp	2	0.14	0
Splinter	Medium	Micro-macro pattern	Regular	Yes	Sharp	4	0.39	4
Flecktarn	Medium	Micro-macro pattern	Irregular	Yes	Smooth	5	0.33	5
Frog-skin	Medium	Medium pattern	Irregular	Yes	Sharp	4	0.33	4
Tiger-stripe	Medium	Micro-macro pattern	Irregular	Yes	Sharp	4	0.16	4
Woodland	High	Macro pattern	Irregular	Yes	Sharp	4	0.28	5
Digital	Medium	Micro-macro pattern	Irregular	Yes	Smooth	4	0.29	5
MultiCam	High	Micro-macro pattern	Irregular	Yes	Sharp and color gradient	7	0.44	7

shards of glass or other brittle matters and includes rain straits [27]. The element diversity of this pattern is not high as it contains only several polygons. This pattern can be classified as a micro-macro pattern due to the presence of rain straits. However, because of the alignment and regularity of the rain straits, they could not improve the camouflage efficiency. The contrast between elements is medium, so this pattern is not a high disruptive pattern. The pattern contains hard-edges between polygons and there are not any color gradients or smooth edges. This pattern has four colors to resemble the colors of leaf, wood, and ground but the shape of its elements is not similar to terrains objects. Therefore, the splinter pattern has many weak points based on the fundamental factors. So, we classified this pattern as an inefficient pattern whereas it has the second rank between other patterns based on the WSSIM index.

B.3. Flecktarn Pattern

Flecktarn has been issued by Germany and it means camouflage with spots [28]. This pattern consists of many spots that are similar to circles so that it is famous as a mottled pattern. Small spots join in some places and make larger spots. Therefore, Flecktarn has small and large spots, which create a medium diversity of elements shape. As for the element size, the presence of micro-macro elements provides multi-scale camouflage. The random distribution of spots over the background is a positive feature of this pattern. Due to joining spots with black and light colors, this pattern has a disruptive feature.

The spots in the Flecktarn pattern make a dithering effect that omits the sharp edges between colored patches. Five different colors of Flecktarn are suitable for temperate woodland terrain [28]. As the base element of Flecktarn is the spot, so the pattern does not match terrain objects effectively. This pattern has the fourth rank between other patterns based on WSSIM index. Therefore, based on the determined total score, this pattern was classified as moderately efficient.

B.4. Frog-skin Pattern

The Frog-skin pattern inspired by the disruptive skin of the frog and was the first effort of the United States military forces to generate a disruptive pattern [29]. Similar to the Flecktarn pattern, the Frog-skin is renowned as a mottled pattern. Therefore, this pattern contains many similar spots that consists of the medium diversity of elements. By focusing on the pattern, it is clear that the element size distribution is not very broad and the elements are apart from each other with sharp edges, so the spots do not form a multi-scale camouflage. While the mottles are randomly placed, the low diversity in the elements would be considered as a negative point in this kind of pattern. The elements shape is similar to the frog skin so it is not a good match for woodland terrains. Finally, this pattern obtained 4 factors out of 7, and thus it was placed in the inefficient category whereas this pattern has the third rank based on the WSSIM index.

B.5. Tiger Stripe Pattern

Tigerstripe's name is derived from the resemblance of the pattern to a tiger's stripes. The elements of this pattern are narrow stripes that look like brushstrokes of brown and khaki, and broader stripes of black over a green background. As these brushstrokes are repeated all over the pattern, it can be said that the element diversity is not very high. There are small and large stripes, which create a micro-macro pattern. The randomly drawn brushstrokes over the background create an irregular pattern. As for many broad black stripes, this pattern is a highly disruptive pattern that may destroy the background matching. Therefore, the contrast between pattern elements should be similar to the contrast of background objects. The different brushstrokes interlock rather than overlap and create sharp edges in the pattern [30]. The shape of elements is not very similar to the terrain objects. The WSSIM index of this pattern is very low comparing to other patterns. Therefore, this pattern achieved 4 factors out of 7, and thus it is an inefficient pattern.

B.6. Woodland Pattern

This pattern has different elements that are inspired by leaves and wood [31]. The size of elements of this pattern is large and it can be classified as a macro-pattern. So, this pattern is not successful at close ranges of distance because there is not any micro-element on it. The different elements placed irregularly in the pattern and based on Fig. 1 there are contrasting elements that disrupt the outlines. As for the type of edges, the internal edges of the pattern are sharp. There are four different colors including green and brown to resemble the leaf and wood, khaki color for matching the ground and black has a contrasting effect. The WSSIM index of this pattern was 0.28 that is a medium value between other patterns. The lack of microelements and color gradient are the imperfections of the woodland pattern. Therefore, as the Woodland pattern achieved 5 factors out of 7, it was considered as a moderately efficient pattern.

B.7. Digital Pattern

A digital pattern makes from square pixels and the pixels join together to make bigger patches. As the basic elements of the digital pattern are pixel and aggregated pixels, the element diversity of this pattern is not high. Two well-known properties of the digital pattern that made it popular are smooth edges that look like dithering to avoid sharp edges formation and micro-macro pattern to provide multi-scale camouflage. The pixels join together randomly in some places of the pattern to avoid regularity but the use of square pixels may create a little regularity in the pattern. This pattern has internal contrasting colors i.e. black and khaki colors, which provide disruption. Four colors in this pattern are similar to terrain colors but the square shape is not a good match for woodland objects. Eventually, it should be noted that the operational wars proved that the digitalization of a pattern is not an effective property for camouflage patterns [32]. However, it can be concluded that the digital pattern is moderately efficient, as it obtained 5 scores out of 7.

B.8. MultiCam Pattern

This pattern contains many different elements that have various sizes so that this pattern is a micro-macro pattern and provides multi-scale camouflage. The elements of the pattern are irregular and distributed randomly over the background. There are light and dark colors in the pattern that makes contrasting elements and cause a disruption effect. The internal edges of this pattern are sharp and smooth. Indeed, there are color gradients in this pattern; while other patterns do not have this feature. Furthermore, the pattern contains seven different colors, which is the maximum quantity of colors between other patterns that make more resemblance to the objects of terrains. MultiCam has the first rank between the selected patterns based on the WSSIM index. Consequently, the MultiCam pattern achieved the maximum score i.e. 7, and thus it is an efficient pattern.

V. CONCLUSION

In this study, we extracted the principles and strategies of camouflage in nature and named them as camouflage fundamental factors. Therefore, we proposed a novel approach based on the defined factors to evaluate the effectiveness of the camouflage patterns. In practical test of our idea, a dataset of customary camouflage patterns and woodland terrain images were collected and their effectiveness was determined based on the level of camouflage factors and WSSIM index. It was concluded that an efficient camouflage pattern should contain several camouflage factors such as various elements, micro-macro pattern, internal irregularity, disruption, sharp and color gradient, and background similarity. Furthermore, the results showed that quantitative methods like WSSIM only cover one camouflage factor i.e. background similarity. For example, despite the high WSSIM index of some camouflage patterns, they are classified as inefficient patterns as they do not contain sufficient camouflage factors. In fact, the computable indexes are valuable for evaluation but they are insufficient, as they do not cover all the requirements of camouflage and concealment. A computable method like WSSIM that calculates the structural similarity based on the pixel intensity of two images is not an exact method for evaluation of camouflage effectiveness. Therefore, to perform an accurate evaluation of camouflage patterns, the researchers should consider the fundamental features of camouflage in addition to the similarity index of pattern and background image. Finally, our research enables new insights into the camouflage evaluation methods to present a more precise computable algorithm by quantifying the fundamental camouflage factors.

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REVIEW PAPER

Role of Fabric Structure on the Second Tensile Elastic Modulus of Net Warp-Knitted Fabrics

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***Abstract*- This work aimed to study the second elastic modulus of net warp-knitted fabrics (NWKF) experimentally and theoretically. Net knitted fabrics were selected to study owing to their wide practical application and also lack of enough attention. Knitted fabrics have two regions of tensile elastic behavior which the initial one refers to the displacement of the elements of fabrics before jamming of the yarns. As soon as jamming takes place completely, the constituent yarns in the structure of fabrics go through tension. In other words, yarns in their spatial configuration resist the applied loads. This resistance is important in the ultimate strength of the fabrics and also in the composite materials reinforced with knitted fabrics. NWKFs were produced using a Raschel knitting machine. Uniaxial tensile tests were conducted in the course and wale directions. The second elastic modulus was measured using a statistical approach. In the theoretical part, a mechanical model based on the configuration of elements of fabrics after jamming status and using Energy method and Castigliano's Theorem was proposed. The proposed model was used to calculate the second elastic modulus. To validate the model, the authors' experimental data along with the collected data from the other researches were compared with the calculated values, and the results showed that the proposed model can predict the modulus reasonably. The results showed that the fabric structure including wale spacing, course spacing, and the number of lapping movements creating the holes affects the second elastic modulus despite the accepted concept, but the mechanical properties of yarns only influence the second elastic modulus of the fabrics.**

***Keywords*: net warp-knitted fabrics, second elastic modulus, uniaxial tests, energy method, castigliano theorem**

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I. INTRODUCTION

Warp-knitted fabrics have been found various applications in different industries and the demand for them has continued to rise. They generally have applications in civil and construction, automotive, and aerospace. Moreover, light-weight composites and medical applications like elastic knitted bands that are widely used in rehabilitation and prophylactic goods are the other usages [1-3]. One of the most advantages of the warp-knitting technique is that net fabrics can be produced simply and without any special equipment. Furthermore, knitting is particularly suitable for the rapid manufacture of components with complex shapes due to the low resistance to deformation of knitted fabrics [4]. In addition to apparel and household textiles, net warp-knitted fabrics (NWKFs) are usually used for preformed composite materials whether using cement or resin matrices. Hence, the study of the physical and mechanical properties of these kinds of fabrics is important. Although net warp-knitted fabrics have many practical applications, there are seldom in-depth studies of their characteristics. Different fabrics have various structures that have been made from different materials. The knowledge of the material is extensive and therefore it is necessary to recognize the geometry of fabrics carefully to investigate their behavior. It should be noted that the fabrics are structures that can resist and transmit applied loads [5]. There are a few research studies in the field of tensile properties of warp-knitted fabrics due to their structural complexity [1,6-12]. However, compressive properties of warp-knitted fabrics, especially spacer ones have been the subject of many pieces of researches [13-15]. In recent years, a few papers have been published to determine the spatial configuration and geometry of knitted fabrics using computer modeling which helps researchers to simulate fabrics and study their behavior before production to prevent waste of time, cost, and effort [16]. Most of these researches are about common knitted fabrics and net fabrics are rarely considered in the literature. When a fabric is subjected to uniaxial forces, two elastic regions can be considered in their load-extension diagrams. It is important to note that there is an unstable transition region between them. The initial elastic region refers to the displacement of the fabric structure in the direction of the applied load. In other words, the initial elastic behavior is the result of the deformation of loops in the direction of the applied load until jamming of yarns takes place. After the jamming happened, the constituent yarns go through tension and the behavior of the fabric as a structure is the sum of the resistance of the yarns. After the second elastic region, yarns were stretched and the breakage of the fabric happened as a result of yarn breakage. Most of the papers address the initial elastic behavior, however, the second elastic behavior is very important for the investigation of composite materials reinforced with knitted fabrics.

As it was revealed, a rare publication is available on theoretical and experimental studies on the tensile properties of net warp-knitted fabrics. Furthermore, the second linear modulus is rarely taken into account. Therefore, this work is intended to investigate the second elastic behavior of net warp-knitted fabrics with two approaches. In the experimental part, NWKF was produced and uniaxial tests were conducted. In the theoretical part, a mechanical model was proposed using Energy method and Castigliano's theorem to calculate the second elastic modulus.

TABLE I
CHARACTERISTICS OF THE USED YARN

Yarn type	Linear density (tex)	Elastic modulus (gf/tex)
PET spun yarns	18.5	242.9

II. EXPERIMENTAL

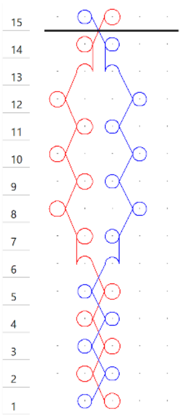
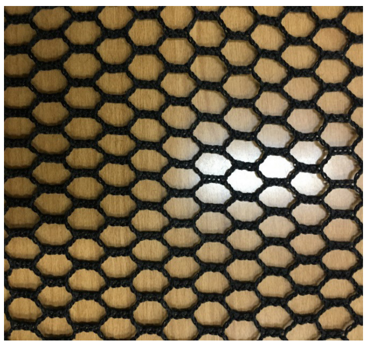
A. Fabric Preparation

A Rachel knitting machine with the gauge eight and two-guide bar was used for producing the net fabrics. Commercial staple PET yarns with negative let-off motion were used for fabric production. The characteristics of yarns are shown in Table I. The lapping movement, produced fabric, and its physical and dimensional properties are shown in Table II.

B. Tensile Tests

To measure the second elastic modulus of the produced fabrics, uniaxial tensile tests were conducted in the course and wale directions. Since there are scarce approved code and methods for determining the specimen size and test speed, samples were examined using the suggested approach [18]. According to the considerations in the used approach, the tests were carried out with a test speed of 50 mm/min, specimen width of 70 mm, and a gauge length of 150 mm. The tensile tests were repeated five times for each specimen.

TABLE II
CHARACTERISTICS OF THE PRODUCED FABRIC

Fabric	Lapping movement[1]	CPC[2]	WPC[2]	Weight[3] (g/m²)	Produced fabric
Net warp-knitted		11.42	3.01	73.08	

[1] The lapping movements were created using the TexMind Warp Knitting 3D software [17].
[2] The values were measured according to ASTM D8007-15e1.
[3] The values were measured according to ASTM D3776-96 (2002).

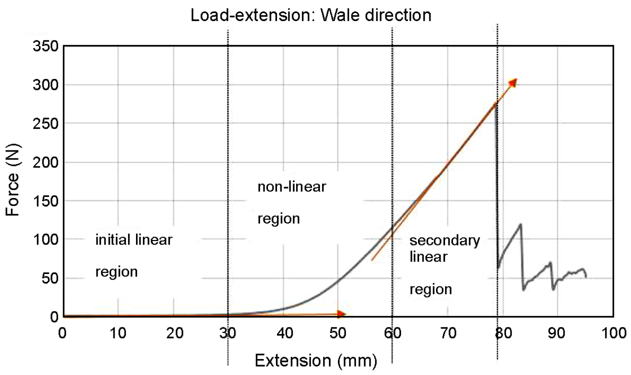


Fig. 1. Typical load-extension diagram of NWKF.

C. Theory

As it was mentioned before, knitted fabrics have two regions of elastic behavior with an unstable transition area between them (Fig. 1). When a fabric is subjected to the action of forces, the geometrical deformation will happen up to the jamming state of the constituent yarns. After jamming takes place, two situations will be arisen based on the structure of fabrics: a) the oblique sides of hexagonal in the determined unit cell of the fabric (Fig. 2a) which become straight after the jamming state, will be under the tension and the constituent yarns of loops creating the sides of hexagonal will deform; b) the yarns creating the loops will resist the applied load and now the elastic modulus of yarns is the dominant factor. The situation "a" happens in the present work, i.e. the sides of hexagonal which were oblique become straight and will be under the forces and this is the situation which refers to the second elastic modulus of the fabrics

When the fabrics are subjected to the action of forces and after the jamming state of the yarns, the shape of the structure of fabrics changes. The hexagonal shape of the holes becomes rectangular during the application of course-wise forces. However, the holes almost become closed and their sides are aligned with the wale-wise loads. Figs. 3 and 4 show the configuration of the unit cell (the hole) and its sides while the second elastic region begins to

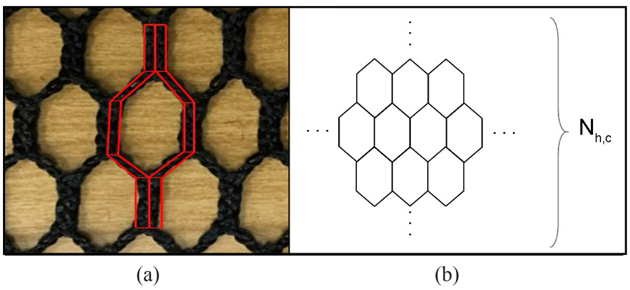


Fig. 2. Structure of the produced fabric: (a) unit cell and (b) the number of holes in the course direction.

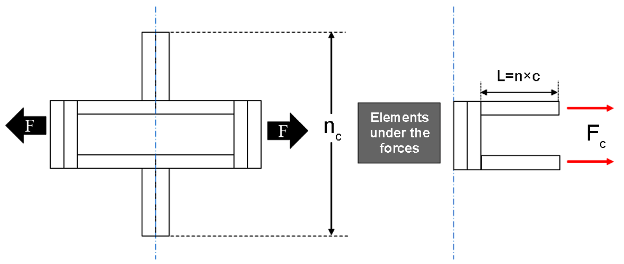


Fig. 3. The unit cell of the fabrics in the course-wise forces after jamming of the yarns: (a) unit cell aligned in the direction of forces and (b) elements used for development of the model.

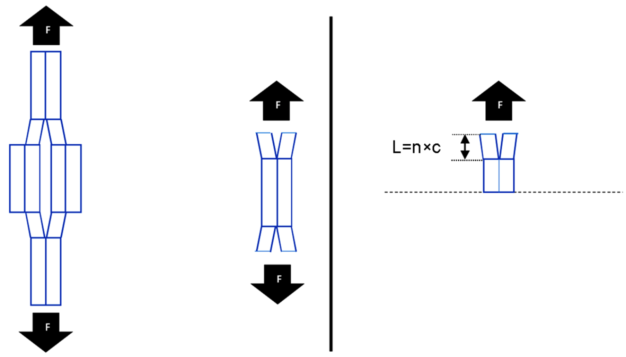


Fig. 4. The unit cell of the fabrics in the wale-wise forces after jamming of yarns: (a) unit cell aligned in the direction of forces and (b) elements used for development of the model.

happen during the application of forces in the course and wale directions, respectively.

Based on the straight-line model for two-guide bar knitted fabrics [6], the shape of loops before and after the action of the course-wise applied loads is shown in Fig. 5. When a given fabric which has been under the action of forces in the course direction reaches the jamming condition, then the structure will be in forces. To propose the models, the following assumptions were made:

1. Yarns have circular cross-sections;

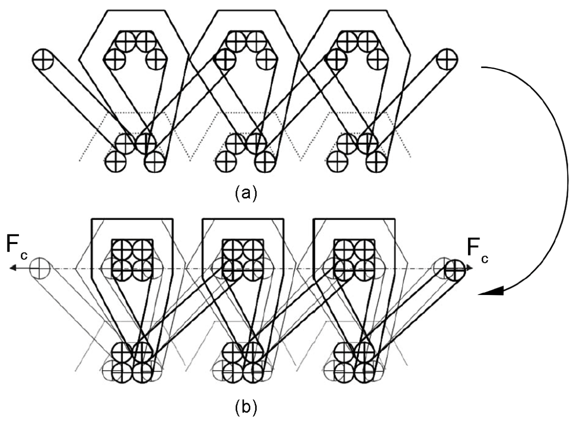


Fig. 5. Shape of the loops: (a) before action of forces and (b) after action of forces [6].

2. Yarns are inextensible and incompressible;
3. Friction between the yarns is neglected.

Assuming the geometry of the fabrics and the determined unit cell, we have:

$$F_{u,c} = \frac{F_{T,c}}{N_{h,c}} \quad (1)$$

$$N_{h,c} = n_c.c \quad (2)$$

In which, $F_{u,c}$ is the force applied to the unit cell in the course direction, $F_{T,c}$ is the force applied to the fabric in the course direction, $N_{h,c}$ is the number of holes counted in the course direction, n_c is the number of course spacing in a hole, and c is the course spacing (1/course per centimeter). It is well known that the fabric extension in course direction (ε_c) is equal to:

$$\varepsilon_c = \frac{\delta W}{W} \quad (3)$$

Where,

$$W = n.c \quad (4)$$

In which W is the wale spacing (1/wale per centimeter), δW is the change in the wale spacing, and n is the number of course spacing. Since the oblique sides of the unit cell became straight as a result of the applied load (secondary linear region), the direction of the sides was changed and the loops creating the sides are horizontal now. Therefore, W is equal to the multiplication of n and c. W can be calculated based on the variation of the direction of sides of hexagonal which are now straight and their lengths are in the size of several course length depending on the lapping movements. Considering the elastic behavior and Hook's law, we have:

$$\delta W = \frac{\sigma_c}{E_c}.n.c \quad (5)$$

The variation of W can be obtained using Castigliano's theorem too. It is equal to:

$$\delta W = \frac{\partial U}{\partial F_{T,c}} = \frac{\partial U}{n_c.c.\partial F_{u,c}} \quad (6)$$

In which, U is the elastic strain energy stored in the fabrics subjected to the axial loads in the course direction.

Equating the Eqs. 5 and 6, we have:

$$\frac{1}{E_c} = \frac{w.d}{n_c.n.c^2.F_{u,c}} \times \frac{\partial U}{\partial F_{u,c}} \quad (7)$$

Where,

$$F_{u,c} = \sigma_c.(w.d) \quad (8)$$

Where, d is the yarn diameter. There is an unknown term, U, in Eq. (7) which can be ascertained using Energy method. When the fabrics are under the axial force in the course direction, tensile stress has the dominant effect and therefore strain energy of elements can be calculated as follows:

$$U = \int_0^L \frac{\sigma_c^2.A.dx}{2E_{yarn}} \quad (9)$$

By integration of U along the length of the straight elements, the strain energy can be concluded:

$$U = \frac{n_c^2.c^2.F_{u,c}^2.L}{2.A.E_{yarn}} \quad (10)$$

Where,

$$\sigma_c = \frac{n_c.c.F_{u,c}}{A} \quad (11)$$

In which A is the cross-section of the specified area of the unit cell under the tensile forces.

Substituting Eq. (10) into Eq. (7) and by differentiation of U with respect to $F_{u,c}$, the modulus of the second elastic region can be calculated as follows:

$$\frac{1}{E_c} = \frac{n_c.w.d.c}{A.E_{yarn}} \quad (12)$$

When the fabric is extended, the shape of loops which forming the structure changes as it was shown in Fig. 5, and then:

$$A = \frac{4.\pi.d^2}{4} \quad (13)$$

Eq. (13) is in accordance with the change in the size of the loops head owing to the application of the forces (Fig. 5). The area which is under the load is four times the area of yarn-cross-section, consequently:

$$\frac{1}{E_c} = \frac{n_c.c.w}{\pi.d.E_{yarn}} \quad (14)$$

A similar procedure can be followed to find the second elastic modulus in the wale direction. There is a marked difference between ascertaining the second elastic modulus in the wale and course directions and it is the constrained elements aligned in the direction of tension. In other words, the area which is under the forces in the wale direction is more than twice the size of the area which was under the forces in the course direction. Using the above-mentioned theory, we have:

$$\frac{1}{E_w} = \frac{w.d}{n_w.n.c.w.F_{u,w}} \times \frac{\partial U}{\partial F_{u,w}} \quad (15)$$

For tensile strain energy in the wale direction, it can be written:

$$U = \int_0^L \frac{\sigma^2.A.dx}{2E_{yarn}} \quad (16)$$

Integrating U along the length of elements, we have:

$$U = \frac{n_w^2.w^2F_{u,w}^2.L}{2.A.E_{yarn}} \quad (17)$$

Where,

$$\sigma_w = \frac{n_w.w.F_{u,w}}{A} \quad (18)$$

Substituting Eq. (18) into Eq. (15) and by differentiation of U with respect to Fu,w, the second elastic tensile modulus in the wale direction can be obtained as follows:

$$\frac{1}{E_w} = \frac{n_w.w^2}{\pi.d.E_{yarn}} \quad (19)$$

D. Other Test Data

The capability of a generally accepted model is that it could deal with a wide range of cases in its studying area. In the present work, the theoretical model was proposed based on the fabric which was produced by the authors. To verify the ability of the model for application in the other kinds of net fabrics, the authors were fortunate to get raw test data of the tensile test of net fabrics from a detailed experimental study [19,20]. The figures and also the physical properties of the fabrics are given in Table III.

III. RESULTS AND DISCUSSION

The second elastic behavior of net warp-knitted fabrics was considered using two approaches namely experimental and theoretical. In the experimental part, uniaxial tensile tests were carried out in the course and wale directions. The second elastic modulus was measured for each test from load-extension diagrams using a statistical method [21]. To determine the tensile moduli values based on the statistical method, the slopes of the load-extension curves at each point with extension levels of pre-defined scale using the nine-point central difference were calculated. These calculations were performed for all the plotted load-extension curves. The data of slopes of each interval were analyzed for significance in differences, using a one-way ANOVA test at the 95% level of confidence. Therefore, the Tukey test was performed to categorize the homogeneous subsets. In the theoretical parts, a mechanical model was

TABLE III
CHARACTERISTICS OF THE FABRICS FROM COLLECTED DATA [20]

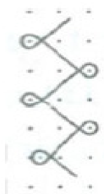
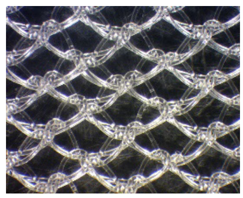
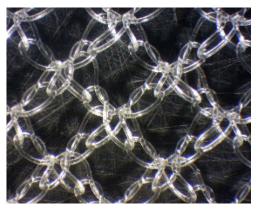
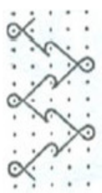
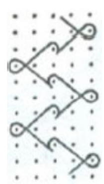
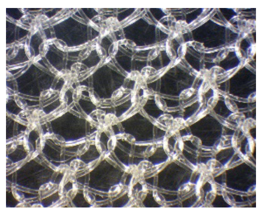
Fabric	Lapping movement		CPC (cm^{-1})	WPC (cm^{-1})	Weight (g/m^2)	Figure of fabrics
	Front guide bar	Back guide bar				
Pinhole net			10	6.2	129	
Sandfly			5.2	5.7	104	
Quasi-sandfly			5.2	6.1	148	

TABLE IV
SECOND ELASTIC MODULUS OBTAINED FROM EXPERIMENTAL INVESTIGATIONS AND THEORETICAL STUDIES FOR NWKF

Fabrics	Test direction	Second elastic modulus (N/mm)		Error (%)
		experimental	theoretical	
Produced fabrics	Course	1.192	1.127	5.453
	Wale	2.145	2.002	6.667
Pinhole-net*	Course	17.169	13.951	18.743
	Wale	12.404	9.514	23.299
Sandfly*	Course	4.775	4.003	16.166
	Wale	10.908	9.143	16.181
Quasi-sandfly*	Course	13.198	9.639	26.966
	Wale	13.466	10.471	22.126

*The experimental data were collected from references 15 and 16.

proposed based on the geometry of fabrics after jamming of the yarns using Energy method and Castigliano theorem. The proposed model was used for the calculation of the second elastic modulus of the fabrics in the course and wale directions.

Since the basic parameters of the fabrics were used to propose the model, it seems that the model can be applied to the other kinds of net fabrics to some extent. The collected data in the form of second elastic modulus, with the authors' own test data, were used to validate the proposed model. The calculated and measured second elastic modulus of the fabrics in the wale and course directions are given in Table IV. As can be seen from the table and also the calculated error, not only the model can predict the modulus of the authors' produced fabric with high accuracy, but also it can predict the modulus of other fabrics reasonably. It is worth mentioning that the errors for the authors' data were minor, however, the errors of prediction for the collected data were further. Furthermore, the calculated errors for sandfly fabrics were smaller than the other collected data. It refers to the structure of the sandfly fabrics that is analogous to the produced fabrics by the authors. The other reason is that the procedure followed for the development of the model was based on the shape of the holes and there is a marked difference between the configurations of the holes of the used fabrics. However, the proposed model could predict the modulus reasonably.

It should be noted that the modulus was obtained through the load-extension diagrams instead of the stress-strain diagrams owing to the point that the cross-sections of fabrics contain an unknown amount of space and thus the cross-sectional area is not clearly defined [22].

The most important result is that the second elastic modulus of the fabrics is a function of the fabric structure. This finding was rarely found in literature owing to the two reasons. First, there is not enough research into the second elastic behavior of the knitted fabrics. Second, most papers relate the second elastic behavior of the fabrics to the yarns mechanical behavior after the jamming status, and the effects of the configuration of yarns in the structure of the fabrics had been ignored. However, the proposed model indicated that the second elastic modulus is not independent of the fabric structure and stitch density, and the size of holes and the length of sides of holes influence the fabric behavior. It is important to note that the effectiveness of the fabric structural parameters is different for wale-wise and course-wise calculations.

IV. CONCLUSION

This study was devoted to investigate the tensile behavior of net warp-knitted fabrics after jamming of the constituent yarns. In other words, the second elastic behavior of fabrics in the course and wale directions was studied experimentally and theoretically. It is important to note that the second elastic modulus is important in the field of composite materials reinforced with the fabrics. Net-fabrics were used due to the lack of enough attention. A theoretical model was proposed based on the consideration of the geometry of fabrics after the jamming of the yarns. Energy method and Castigliano theorem were used to build the model. To assess the proposed model, uniaxial tensile tests in the wale and course directions were conducted. Furthermore, the experimental data from the other researches were used for validation of the proposed model. The results indicated that the mechanical model can predict the second elastic modulus sufficiently. This work showed that not only the second elastic modulus of knitted fabrics is the function of yarn modulus but also the structure of fabrics like stitch density, the size of holes, and the length of sides of holes affect the modulus considerably. This result was true despite the heretofore accepted concept.

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REVIEW PAPER

Maximum Negative Poisson's Ratio of Double-Core Helical Auxetic Yarns Under Uniaxial Loading: A Study on the Effect of Structural Parameters via Full Factorial Experimental Design Method

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***Abstract*- Auxetic textiles have been attracted the attention of many researchers due to their enhanced mechanical behavior during loading condition. The developed Double-core helical auxetic yarn (DC-HAY) is a structural material with negative Poisson's ratio (NPR) behavior. It consists of two similar soft yarns with a higher diameter and a stiff yarn with a lower diameter. The stiff yarn has been twisted around the soft yarns, alternatively. In this paper, the effect of structural parameters including, the initial helical angle of wrap component with five levels, diameter ratio of components with three levels, and modulus ratio of components with two levels, on Poisson's ratio of DC-HAY, has been investigated through the full factorial experimental design method. SPSS software has been used for analyzing the results. The results showed that the highest maximum NPR belongs to the sample with the lowest initial helical angle, highest diameter ratio of components, and highest modulus ratio of components. Also, it has been found that all the main factors have a statistically significant effect on Poisson's ratio of DC-HAY at a 95% of confidence level.**

***Keywords*: double-core helical auxetic yarn (DC-HAY), negative Poisson's ratio (NPR), image processing, full factorial**

I. INTRODUCTION

Auxetic materials are metamaterials with interesting properties that do not exist in common materials. Such material expands laterally under tensile loading and contracts latterly under the compression loading. Compared to common materials, they exhibit high in-plane shear modulus, high indentation resistance, high fracture resistance and low crack propagation, synclastic curvature, strain dependable porosity, high energy absorption, etc. These extraordinary properties made them suit for application in the field of aerospace, automotive, biomedical, composites, military, sensors/actuators, and textiles [1]. Auxetic textiles are known as one of the most favorable structural materials for developing auxetic behavior due to their structural variability and high material adaptability. Auxetic textiles are in three main forms; fibers, yarns, and fabrics. These forms are using in various products for different purposes. For example, fiber or yarn forms of auxetic textiles can lock the textiles in position during the tensile loading of textile reinforced composites, and fabric form can reduce drag delivery according to swelling decreases during the wound healing [2]. Auxetic yarns, besides the simplicity of their production process, have several advantages over conventional ones. During the three past decades, many forms of auxetic yarns such as the helical auxetic yarn (HAY) [3], semi-auxetic yarn (SAY) [4], auxetic plied yarn (APY) [5], braided auxetic yarn (BAY) [6], interlaced-helical wrapping yarn (IHWY) [7], braided yarn with helical auxetic yarn [8], and double-core helical auxetic yarn (DC-HAY) [9], have been introduced by scholars. Hook *et al.* proposed the first auxetic yarn, namely the helical auxetic yarn (HAY), combined with one soft fat yarn as a core component and a stiff thin yarn, twisted around it, as a wrap component. When the HAY is under the uniaxial tensile loading, the wrap component dominates the core component and starts to get straight due to its higher young modulus. This kind of deformation leads to expansion transversely non-uniform under tensile

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loading and results in auxetic performance. This type of yarn also can be produced by the conventional method of spun-yarns [3]. Du *et al.* conducted a theoretical study to present a geometrical model for predicting the Poisson's ratio of HAY under various amounts of structure strain and understanding the auxetic performance of HAY. The diameter of components, Poisson's ratio of components, and the initial helical angle of the wrap component were considered as the input parameters of the model. In the model, the whole tensile process is divided into two regions according to a criterion called "critical strain". The critical strain is the strain of structure that wrap component gets fully straighten before getting any elongation. The predicted amounts of Poisson's ratio versus axial strain showed the same trend as the experimental ones, but the values obtained through the theoretical model were much higher than the experimental ones because of considering the geometrical effect solely. They also simulated the HAY through the ABAQUS software to investigate the structural parameters on Poisson's ratio of structure. Despite the similar results, the numerical values were closer to experimental ones due to considering both materials and geometrical effect [10,11]. Sibal and Rawal presented a theoretical model based on the energy minimization approach for predicting Poisson's ratio of the HAY during tensile loading. According to their proposed model, the potential elastic energy stored in each component has been divided into tensile, shear, bending, and torsion terms. Based on their conclusion, the auxetic effect occurs under a strain level at which the bending term tends to dominate over the tensile term. Also, a "balanced" HAY having the same initial helical angles of wrap component and core components can be developed at a defined level of axial tensile strain when the torsion term of energy is the same as that of the corresponding shear term. The comparison results between the predicted values and the ones related to the experimental works showed a good agreement [12]. Kwietniewski and Miedzinska performed a numerical study through ABAQUS software for investigating the effect of structural parameters on the tensile properties of HAY. The results of the comparison of the true stress-true strain curve between predicted and experimental values showed a good agreement [13]. Liu *et al.* conducted a theoretical work for studying the effect of structural parameters on the tensile properties of HAY. According to their studies, pressure and friction between the components of HAY exist during the deformation. They tried to present a rheological model to analyze the structuring effect on the tensile properties of HAY. The comparison results showed a good agreement with a correlation coefficient of higher than 0.97 between the predicted and experimental values [14]. Razbin *et al.* tried to modify Du's model by replacing a new criterion called "jamming strain" instead of "critical strain". According to their study, the wrap component forms a helix with a radius equals to its initial radius at the jamming strain. They also suggested a function instead of a constant representing the non-linear Poisson's ratio behavior of the core component. The results showed significant improvement in prediction [15]. The same research courses have been conducted for auxetic plied yarn [16-18], braided auxetic yarn [19,20].

The scholars are trying to understand the deformation behavior of auxetic yarns during the tensile loading using different methods. To the best knowledge of the authors, despite the available reports concerning the experimental, numerical, and theoretical studies for auxetic yarns in the literature, there is no work on the statistical analysis of these structures. In this work, we undertake an experimental investigation on the maximum negative Poisson's ratio (NPR) of DC-HAY statistically via the full factorial experimental design method.

II. EXPERIMENAL

A. Materials and Experimental Design

In this study, three same types of monofilament core yarns with different diameters and two different types of monofilament warp yarn with the same diameter have been selected to produce the DC-HAY. To specify the mechanical properties of components, a tensile test according to ASTM D3822-01 via a testing device (Instron 5566) under the constant rate of elongation at 200 mm/min and a gauge length of 250 mm was conducted. The specifications of

TABLE I
SPECIFICATIONS OF COMPONENTS

Component	Type	d (mm)	E (MPa)	σ_u (MPa)	ε_{rup} (%)	ν
Core-1	Rubber	3.85±0.21	0.92±0.06	1.81±1.51	197.65±3.10	0.49
Core-2	Rubber	5.72±0.19	1.24±0.18	1.77±0.12	142.47±2.14	0.49
Core-3	Rubber	8.62±0.32	1.12±0.11	1.68±0.10	160.18±1.98	0.49
Wrap-1	Nylon 6	0.500±0.00	1667.53±2.14	414.23±3.49	29.31±1.41	0.42
Wrap-2	Copper	0.500±0.00	5060.34±4.10	273.32±1.37	44.25±0.50	0.36

TABLE II
EXPERIMENTAL DESIGN

Sample	Core yarn	Wrap yarn	θ_{actual} (degree)	d_c/d_w (mm/mm)	E_w/E_c (MPa/MPa)
A-1	Core-1	Wrap-1	15.16±0.94	7.70	1812.53
A-2	Core-1	Wrap-1	20.29±1.59	7.70	1812.53
A-3	Core-1	Wrap-1	26.19±0.75	7.70	1812.53
A-4	Core-1	Wrap-1	35.32±1.95	7.70	1812.53
A-5	Core-1	Wrap-1	42.19±1.39	7.70	1812.53
B-1	Core-2	Wrap-1	15.16±0.94	11.44	1344.78
B-2	Core-2	Wrap-1	20.29±1.59	11.44	1344.78
B-3	Core-2	Wrap-1	26.19±0.75	11.44	1344.78
B-4	Core-2	Wrap-1	35.32±1.95	11.44	1344.78
B-5	Core-2	Wrap-1	42.19±1.39	11.44	1344.78
C-1	Core-3	Wrap-1	15.16±0.94	17.24	1488.87
C-2	Core-3	Wrap-1	20.29±1.59	17.24	1488.87
C-3	Core-3	Wrap-1	26.19±0.75	17.24	1488.87
C-4	Core-3	Wrap-1	35.32±1.95	17.24	1488.87
C-5	Core-3	Wrap-1	42.19±1.39	17.24	1488.87
D-1	Core-1	Wrap-2	15.16±0.94	7.70	5500.37
D-2	Core-1	Wrap-2	20.29±1.59	7.70	5500.37
D-3	Core-1	Wrap-2	26.19±0.75	7.70	5500.37
D-4	Core-1	Wrap-2	35.32±1.95	7.70	5500.37
D-5	Core-1	Wrap-2	42.19±1.39	7.70	5500.37
E-1	Core-2	Wrap-2	15.16±0.94	11.44	4080.92
E-2	Core-2	Wrap-2	20.29±1.59	11.44	4080.92
E-3	Core-2	Wrap-2	26.19±0.75	11.44	4080.92
E-4	Core-2	Wrap-2	35.32±1.95	11.44	4080.92
E-5	Core-2	Wrap-2	42.19±1.39	11.44	4080.92
F-1	Core-3	Wrap-2	15.16±0.94	17.24	4518.16
F-2	Core-3	Wrap-2	20.29±1.59	17.24	4518.16
F-3	Core-3	Wrap-2	26.19±0.75	17.24	4518.16
F-4	Core-3	Wrap-2	35.32±1.95	17.24	4518.16
F-5	Core-3	Wrap-2	42.19±1.39	17.24	4518.16

the components have been listed in Table I. According to Table II, an experiment with factorial design including five, three and two levels of the initial helical angle of wrap component, diameter ratio of components and young modulus ratio of components has been conducted, respectively. Experiments were carried out under conditions of 22 °C and 65 RH% and to ensure the results, five repetitions for each combination have been considered until rupturing.

B. Production and Measurement

Fig. 1a shows the schematic structure of DC-HAY which is constructed by combining two same soft yarns with a higher diameter as core components and a stiff yarn with a lower diameter as wrap components that alternatively has been twisted around the core yarns. The samples were produced manually according to primary calculations based on the diameter of the component, pitch length and helical angle of the wrap component. Then, the actual helical angle of the wrap component was measured using

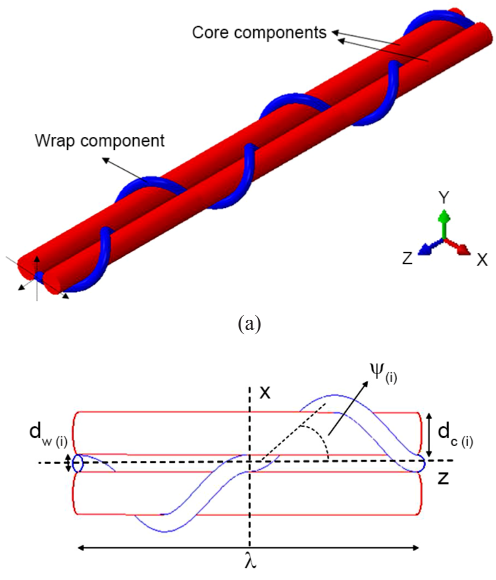


Fig. 1. Structure of DC-HAY at initial state: (a) schematic illustration and (b) geometrical parameters.

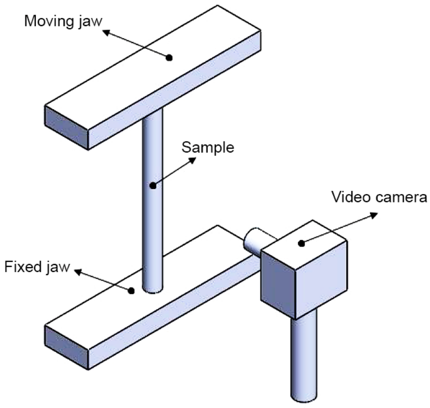


Fig. 2. Tools assembly of measuring the Poisson's ratio of helical auxetic yarn.

Digimizer software for further analysis.

The below Equations based on the geometry of structure at the initial state (Fig. 1b) have been used for production:

$$\psi_{(i)} = \tan^{-1}\left(2\pi\frac{\left(d_{c(i)}+d_{w(i)}\right)}{\lambda}\right) \tag{1}$$

$$TPM = \frac{1000}{\lambda} \tag{2}$$

Where, TPM, ψ, λ, d_c, and d_w are twist per meter, helical angle of wrap component in degree, pitch length in mm and diameter of the core and the wrap components (mm),

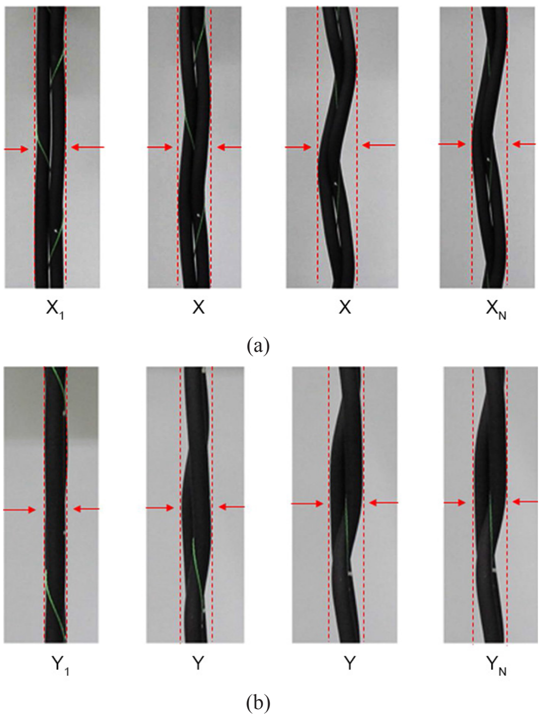


Fig. 3. Deformation of samples during the tensile loading through: (a) "X" direction and (b) "Y" direction.

respectively. The index i refers to the initial state of the structure. To measure the Poisson's ratio of DC-HAY, a tensile tester device (Instron 5566) according to ASTM D3822-01, with elongation speed as 200 mm/min and initial gauge length as 25 cm has been used. To trace the transversal strain of samples a video camera (Cannon PowerShot 530) has been utilized. Tools assembly has been shown in Fig. 2.

According to Fig. 1a, the deformation behavior of DC-HAY can be investigated through "ZX" and "ZY" planes. So, two Poisson's ratio for DC-HAY has been defined as the below equations:

$$\nu_{XZ(n)} = -\frac{\varepsilon_{X(n)}}{\varepsilon_{Z(n)}} \tag{3}$$

TABLE III
RESULTS OF POISSON'S RATIO MEASURMENT

Sample	Response	
	"X"	"Y"
A-1	-11.98±0.41	-11.50±0.31
A-2	-6.32±0.38	-5.97±0.33
A-3	-3.21±0.21	-2.98±0.11
A-4	-1.18±0.17	-1.03±0.11
A-5	-0.60±0.24	-0.53±0.12
B-1	-10.52±0.16	-10.05±0.05
B-2	-6.58±0.24	-6.14±0.18
B-3	-3.28±0.20	-3.05±0.19
B-4	-1.28±0.17	-1.13±0.09
B-5	-0.62±0.31	-0.57±0.13
C-1	-10.24±0.33	-9.93±0.41
C-2	-6.71±0.25	-6.30±0.45
C-3	-3.62±0.21	-3.30±0.11
C-4	-1.73±0.17	-1.33±0.08
C-5	-0.74±0.14	-0.60±0.19
D-1	-12.13±0.51	-11.63±0.24
D-2	-6.69±0.35	-6.12±0.39
D-3	-3.29±0.15	-2.99±0.12
D-4	-1.21±0.15	-1.11±0.40
D-5	-0.64±0.18	-0.58±0.22
E-1	-13.9±0.36	-13.14±0.45
E-2	-7.68±0.52	-7.02±0.20
E-3	-3.96±0.34	-3.41±0.22
E-4	-1.79±0.77	-1.59±0.08
E-5	-0.89±0.11	-0.80±0.19
F-1	-14.50±0.23	-14.17±0.47
F-2	-8.23±0.41	-8.16±0.44
F-3	-4.49±0.17	-4.26±0.19
F-4	-2.01±0.21	-1.87±0.12
F-5	-1.02±0.28	-0.92±0.15

TABLE IV
REASULTS OF ANOVA TEST

Main factors	Type	Levels	Code	Confidence level
Helical angle	Fixed	5	A	95 %
Diameter ratio	Fixed	3	D	
Modulus ratio	Fixed	2	E	

Source	D.F	S.S		M.S		F		P	
		"X"	"Y"	"X"	"Y"	"X"	"Y"	"X"	"Y"
A	4	2630.83	2499.83	657.71	624.96	10500.82	14430.66	0.00	0.00
D	2	11.19	11.32	5.60	5.66	89.35	130.68	0.00	0.00
A*D	8	2.14	3.40	0.267	0.43	4.26	9.80	0.00	0.00
E	1	37.29	29.41	37.29	29.41	595.37	679.11	0.00	0.00
A*E	4	32.13	29.94	8.03	6.74	128.25	155.51	0.00	0.00
D*E	2	11.20	15.86	5.60	6.74	89.43	183.05	0.00	0.00
A*D*E	8	14.12	15.36	1.77	1.92	28.19	44.32	0.00	0.00
Error	120	7.516	5.20	0.06	0.04				
Total	149	2746.43	2607.31						

$$\nu_{YZ(n)} = -\frac{\varepsilon_{Y(n)}}{\varepsilon_{Z(n)}} \tag{4}$$

Where, ε_X, ε_Y, and ε_Z are the strain at "X", "Y", and "Z" directions, respectively. The index (n) indicates the nth step of the calculation. In order to calculate the strain at "Z" direction, the following Equation has been used:

$$\varepsilon_{Z(n)} = \frac{TR(n-1)}{60L_0(N-1)}; \quad n \in [2.N] \tag{5}$$

Where, T is an effective time of the recorded video (s), R is the rate of elongation (mm/min), and L_0 is the initial gauge length (mm). In order to calculate the strain at "X" and "Y" directions, the lateral expansion of samples has been recorded by the video camera. Then, the video film has been divided into N images. In order to process the images, a program based on MATLAB software has been written. The image processing basic that used for the determination of lateral expansion through the "X" and "Y" directions are shown in Fig. 3.

Finally, Eqs. (6) and (7) have been used to determine the maximum NPR of DC-HAY through "ZX" and "ZY" planes, respectively.

$$\nu_{XZ(max)} = \min\left\{\nu_{XZ(2)}, \ldots, \nu_{XZ(i)}, \ldots, \nu_{XZ(n)}\right\} \tag{6}$$

TABLE V
RESULTS OF STUDENT-NEWMAN-KEULS TEST

A	Subset									
Level	1		2		3		4		5	
	"X"	"Y"	"X"	"Y"	"X"	"Y"	"X"	"Y"	"X"	"Y"
1	-12.20	-11.78								
2			-7.03	-6.66						
3					-3.68	-3.33				
4							-1.57	-1.32		
5									-0.73	-0.69
Sig.	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

D	Subset					
Level	1		2		3	
	"X"	"Y"	"X"	"Y"	"X"	"Y"
1	-5.37	-5.12				
2			-5.06	-4.68		
3					-4.70	-4.46
Sig.	1.00	1.00	1.00	1.00	1.00	1.00

$$\nu_{YZ(max)} = \min\{\nu_{YZ(2)}, \ldots, \nu_{YZ(i)}, \ldots, \nu_{YZ(n)}\} \tag{7}$$

III. RESULTS AND DISCUSSION

Table III shows the interval estimation of average maximum NPR of samples at different directions of measurement at 95% confidence level. As can be seen in Table III, the means values of Poisson's ratio increase by reducing the initial helical angle of the wrap component, increasing the diameter ratio of components and increasing the modulus ratio of components. The highest maximum NPR among the samples belongs to the sample F1 for both directions of measurement. In order to analyze the variances, the ANOVA test has been performed using SPSS 23 software and then results for both directions of measurement have summarized in Table IV.

In order to define the subset of the level of the main factors, the Student-Newman-Keuls test has been utilized. According to Table IV, the D.F, S.S, and M.S refer to the degree of freedom, the adjusted sum of squares and adjusted means squares, respectively. The F value of variables has been calculated by dividing the M.S of the variable by M.S of error. The P-value of variables has been calculated based on the area under the appropriate null-sampling distribution of F which is higher than the observed F-statistic [21]. It should be pointed out that the below assumptions during the ANOVA test have been made:

- Normal distribution of population;
- Independent samples;
- Homogeneity of variances.

As can be seen through Table IV, the P-value ($P<0.05$) of all variables indicated that the effect of parameters on the given experimental layout is statistically significant. Based on the S.S value of main factors, the initial helical angle of wrap component and diameter ratio of components have the highest and lowest effect, respectively. Compared to similar previous studies in the case of helical auxetic yarn (HAY) [10-15], it can be found that some main parameters like helical angle, diameter ratio and modulus ratio of components are affecting also the auxetic behavior of DC-HAY. In addition, the effect of combined variables indicated that the main factors have different trends in different levels of each other.

Based on the results of Table IV, there is a statistically significant difference between the modulus ratios of components. In addition, the total levels of this factor is two which does not require to be analyzed through the Student-Newman-Keuls test. The results of the analysis in the case of the initial helical angle of wrap component and diameter ratio of components have been summarized in Table V. It can be seen that there is a statistically significant difference between the selected levels of both factors that the subsets of them are equal to their selected levels. Further analysis has been used to investigate the trend of variation in the case of main factors at both directions of measurement as shown in Fig. 4.

According to Fig. 4 at both directions of measurement, increasing the initial helical angle of the wrap component will results in decreasing the maximum NPR of samples due to increasing the required strain to reach the maximum diameter of structure. Also, increasing the diameter ratio of components will results in a higher maximum NPR due

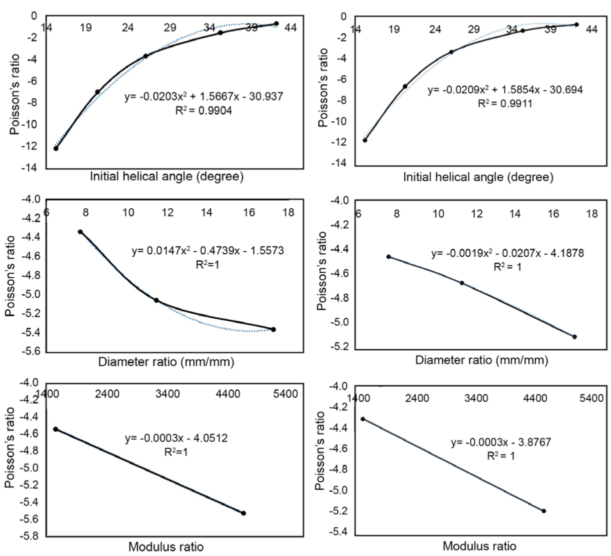


Fig 4. Effects of main factors on Poisson's ratio of DC-HAY: (a) "X" direction and (b) "Y" direction.

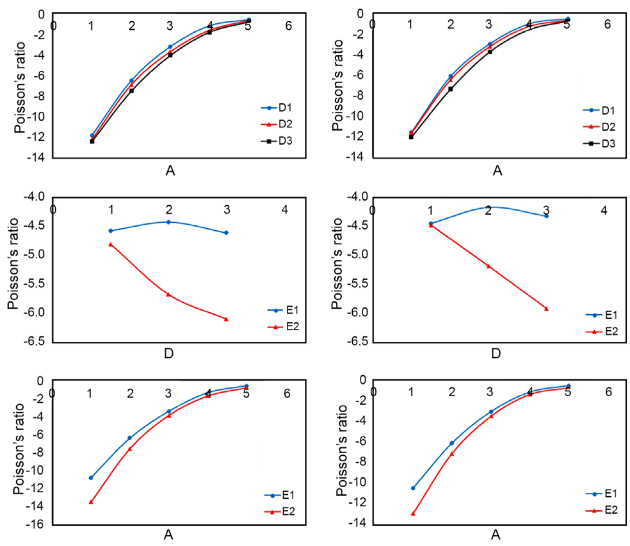
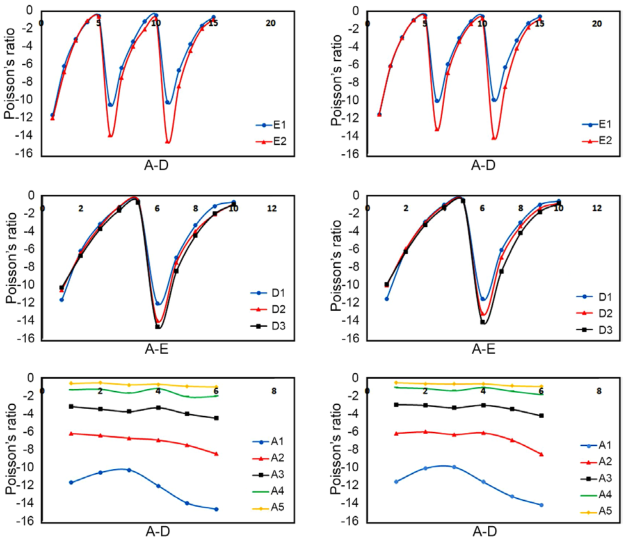


Fig. 5. Two-way interaction between the factors: (a) "X" direction and (b) "Y" direction.



(a) (b)

Fig. 6. Three-way interaction between the factors: (a) "X" direction and (b) "Y" direction.

to increasing the maximum diameter of the structure. The same results as the diameter ratio of the component could be found in the case of the modulus ratio of components. In fact, increasing the modulus ratio of components will increase the predominance of the wrap component over the core components that will result in a higher maximum NPR. Furthermore, the trends of variations indicated that there is a non-linear relationship between the initial helical angle of the wrap component and maximum NPR of structure. The same results could be found in the case of the diameter ratio of the component. There could be no absolute decision about the variation of modulus ratio of components trend due to selected two levels of the factor. When the effect of the interaction of main factors has been studied, the results of the analysis could be found as shown in Figs. 5 and 6. According to the results of Figs. 5 and 6, it could be said that there is interaction including 2-way and 3-way between the factors due to non-parallelism of plots which is in agreement with results of Table IV.

IV. CONCLUSION

In this work, the full factorial method was considered for the experimental design of samples. Some structural variables of samples, such as the initial helical angle of the wrap component, the diameter ratio of components, and the modulus ratio of the components, were considered as the main parameters. According to the statistical analysis, all the main parameters have a statistically significant effect on the Poisson's ratio of the samples. It was found that the initial helical angle of the wrap component has the highest effect on the maximum NPR of the structure at both directions. Also, the results of the ANOVA test showed that the 2-way and 3-way interactions between the factors exist. Finally, it can be deduced that to achieve a higher amount of maximum NPR, a lower amount of initial helical angle, higher diameter ratio of components, and higher modulus ratio of the components, must be considered during the manufacturing process of DC-HAY.

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REVIEW PAPER

Metallocene and Ziegler-Natta Catalysts

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Abstract- **Fifty years ago, Karl Ziegler and Natta won the Nobel Prize for their discovery of the catalytic polymerization of ethylene and propylene using titanium compounds with aluminum-alkyls as co-catalysts. Polyolefins are constantly growing and are now one of the most important high-consumption polymers. New metallocene/methylaluminoxane (MAO) catalysts have made it possible to synthesize polymers with highly defined microstructure, tacticity and steroregularity, such as long chain branched or block copolymers with excellent properties. Melt spinning of the fibers of metallocene-catalyzed isotactic polypropylene (PP) and standard equivalent of Ziegler-Natta isotactic polypropylene and therefore the properties of PP and several thermal and mechanical properties of fiber have been investigated. Ziegler-Natta catalysts were prepared by a reaction method which employed $Mg(OEt)_2$ as a precursor. Newly developed metallocene-catalyzed PP possesses higher isotacticity and crystallinity than commercial ones, so the mechanical properties of the final product are guaranteed.**

Keywords: **Ziegler-Natta, metallocene, polypropylene, catalysts, polyolefins**

I. INTRODUCTION

Nonwoven fabric became a particularly important part of the textile industry. Compare to the global market average of 24%, the Indian market will occupy by 12% of the technical textiles manufactured by nonwoven technology. The nonwoven market is projected to grow from USD 40.50 billion in 2020 to USD 53.5 billion by 2025. For manufacturing of nonwoven fabric, there are different methods used to produce nonwoven fabrics supported by the web formation method, dry-laid nonwoven, spun-laid nonwoven, wet-laid nonwoven, supported web bonding, mechanical bonding, thermal bonding, and chemical bonding. The bonding types, the fiber type and therefore the manufacturing parameters determine the characteristic feature of the nonwoven. In contrast to standard engineering materials, these fabrics have better specific mechanical properties, strength to weight and stiffness to weight ratios [1]. The official definitions are provided by a professional organization like EDANA (European Disposables and Nonwoven Association) or INDA (International Nonwoven and Disposable Association). Melt-blown nonwoven and spun-laid nonwoven are most generally methods used for production of nonwoven fabrics. Melt-blown nonwovens are usually made through a continuous process. Fibers are spun then directly dispersed into a web by deflectors or are often directed with air streams. This method results in a faster belt speed and cheaper costs. Spun-laid nonwoven fabrics also called spun-bond nonwoven fabrics are produced by extruding molten polymer fibers through a spin net or die consisting of up to 40 holes per inch to create long thin fibers which are stretched and cooled by passing hot air over the fibers as they fall from the die. The approaching web is collected into rolls and subsequently converted to finished products. Spun-blown plays the role of imparting strength to nonwoven fabric and melt-blown is employed for barrier properties of nonwoven fabric. Differing types of polymers are utilized in the assembly of nonwoven fabrics like polyesters, polyetylene terephthalate (PET) and polypropylenes, and they are either within the type of small chips form or in the form of powder. Spun-bond/melt-blown/spun-bond, commonly

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called SMS, is a tri-laminate nonwoven fabric. It is made from a top layer of spun-bond polypropylene, a middle layer of melt-blown polypropylene and a bottom layer of spun-bond polypropylene. Polypropylene is a downstream petrochemical product derived from the olefin monomer, propylene. The polymer is produced through a process of monomer connection called addition polymerization normally by using the Ziegler-Natta catalyst system. Ziegler-Natta catalysts are heterogeneous catalysts developed by Karl Ziegler and Natta in 1950, which are utilized in stereospecific catalytic polymerization methods. Isotactic polypropylene resins have been produced from Ziegler-Natta catalysts for more than 45 years. Resins with relatively high molecular mass and relatively wide molecular mass distribution are produced inside the polymerization reactor. Metallocene isotactic PP is a uniform polymer with a relatively narrow molecular mass that is suitable for fiber spinning [2,3].

A. Heterogeneous Catalysts

These are industry-dominating catalysts that are supported titanium compounds (and sometimes vanadium-based) and used for polymerization reactions, usually together with organo-aluminum compounds like tri-ethylaluminium (TEA, $Al(C_2H_5)_3$) as co-catalysts [4].

B. Homogeneous Catalysts

These are the second largest class of catalysts and are supported complexes of Ti, Zr, or Hf. They are generally used in combination with a variety of various organo-aluminum co-catalysts called metallocene/methylaluminoxane (MAO). Traditionally, they include metallocenes but also have multi-dentate oxygen- and nitrogen-based ligands [3].

II. EXPERIMENTAL

A. Manufacturing Process

A.1. Materials

Isotactic polypropylene with metallocene catalyst and Ziegler-Natta catalyst was used for production of melt-spun nonwoven fabrics by using melt-blown thermal bonding method. The commercial metallocene PP was purchased from Lyondell Basell Industries [5].

A.2. Method

For manufacturing of nonwoven fabrics, there are mainly two methods used: melt-spinning and spun-spinning methods. The melt-extrusion spinning was conducted by using a single-screw extruder (Fig. 1) equipped with a metering-pump and eight-hole spinneret, and its diameter was about 0.5 and 0.6 mm. The spun-extrusion spinning was conducted by using a single-screw extruder with a metering pump and six-hole spinneret, and diameter of 0.4 mm. Nonwoven fabric was produced by using spun-blown or melt-blown methods [6].

A.3 Manufacturing Method

The manufacturing method of nonwoven fabric is completed with spun bonding method (Fig. 2) or melt-blown method and sometimes both are combined to make a nonwoven fabric. Spun bonding method is a spun-bond process that was first patented in 1940s and since then it has become more and more popular all over the world with more progress. The technique itself includes fibers being spun then directly being dispersed into a web by deflectors or air streams. They use no chemicals, and are thermo-bonded. This method is preferred because it is cost effective for manufacturers. Over the past 20 years, it is used to make several household products such baby diapers, adult diapers, medical products, protective apparel and hygiene products. Spun-bonds also are flame-retardant or have antistatic properties, and may therefore be used for increased ultraviolet and gamma radiation protection. Many of their features including: low weight, high strength, high air permeability, hydrophilic properties, and excellent wear and tear properties. In addition, with the advancement of this technique, spun-bonds are now much softer and easier than previous types and weigh on average only 10 g/m^2 to

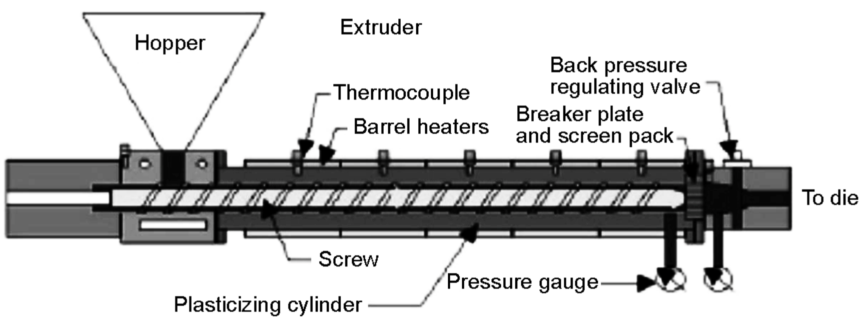


Fig. 1. Extruder.

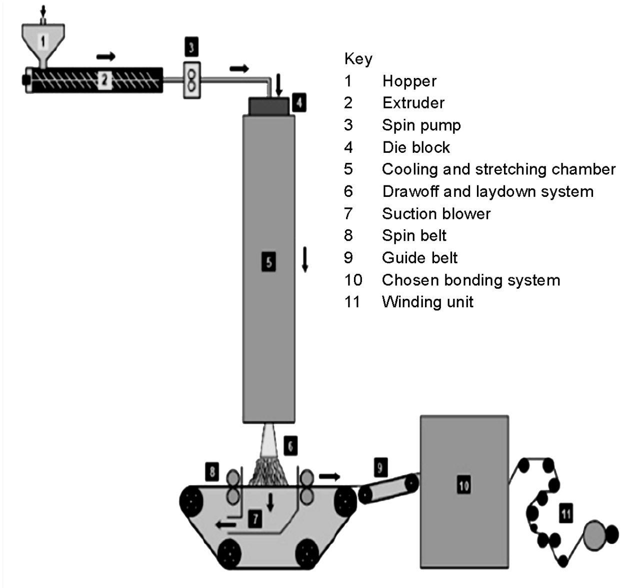


Fig. 2. Schematic of the spun bonding process.

150 g/m^2 [4,7].

A.4. Melt-Blown Method

The melt-blown process came after spun-bond technology and is a process by which ultrafine filament (micro-fibers) nonwovens are often produced at low costs. The technique involves blowing hot air onto the molten thermoplastic, which extrudes through a linear die containing many small holes, creating a fine fibered self-bonded nonwoven web (Fig. 3). Its main feature is that the fiber is very thin. As a result, this material is usually used in filters for air, liquids, and particles, or as absorbents in products like wipes, oil absorbents, incontinence products, and feminine hygiene, but also can be utilized in the production of certain electronics, adhesives, and other apparel [7,8].

A.5. Properties of Fiber

The fiber produced from Ziegler-Natta catalyst PP has long starched on the conveyor belt of the machine through a spun-bond machine and fiber produced from melt-blown are finer than the spun-blown it do not required any types of stretching. The properties of the fabric are presented in Table I.

A.6. Catalysts Preparation

The catalyst sample was characterized using scanning electron microscopy (SEM). It had been evident that

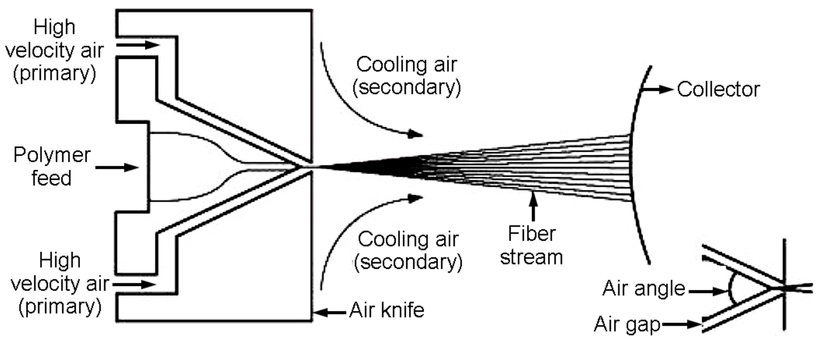


Fig. 3. Melt-blown method.

TABLE I
PHYSICAL PROPERTIES OF POLYPROPYLENE (PP) AND POLYETHYLENE (PE), PREPRINTED WITH PERMISSION FROM [6]

No.	Properties	Polyethylene	Polypropylene
1	Density	0.92-0.95	0.9-0.91
2	Young modulus (GPa)	0.3-1.0	1.4
3	Glass transition temperature (°C)	-125 to -80	-20
4	Limiting oxygen index, LOI (%)	18	17
5	Melting temperature (°C)	112-134	160
6	Specific heat capacity (J/kg.K)	1750-2400	1900
7	Stiffness to weight ratio: tensile (MN.m/kg)	0.32-1.0	1.2-1.5
8	Tensile strength (MPa)	7-49	23-36

there was no significant change in morphologies upon the immobilization of the catalyst. $TiCl_4/MgCl_2$ catalyst was prepared by recrystallization method through reacting $MgCl_2$-ethanol adduct with $TiCl_4$ by the following procedure: 2 g (0.0210 mol) of anhydrous magnesium dichloride was suspended in 100 mL of heptane and 0.1259 mol of ethanol was added dropwise. Then, the solution was stirred for two hours, and 28 mol of aluminum compound was introduced dropwise and heated to 90 °C and hold for 2 h. Thereafter, 0.0255 mol of titanium tetrachloride was added and therefore the mixture was stirred for two hours. Finally, the catalyst obtained was washed with heptane for several times [9].

A.7. Polyethylene and Polypropylene

Currently, polyethylene (PE) is one of the preferred and widely used polymers. The formation of PE occurs by the polymerization of the ethylene monomer in an insertion reaction. Despite the easy structure of PE, its fabrication process is complex and consists of various types of synthetic methods. Due to a number of special features, it is considered as a new polymer with high crystallization rate and flexible chains, which is mostly due to its complete chain structure. Therefore, it is not available in an amorphous state and most of its properties are derived by extrapolating from those of semi-crystalline samples. The properties of various types of PE can vary as a consequence of structural changes resulting from the polymerization technique. Generally, linear low density polyethylene (LLDPE), and high density polyethylene (HDPE) are conventionally synthesized via the catalytic ethylene polymerization reaction at low temperatures and pressures, as compared to the LDPE manufacturing route. Especially, LLDPEs prepared via Ziegler-Natta catalysts have more uneven co-monomer distributions, whereas, a reverse trend is observed for those synthesized by metallocene catalysts. Such differences in co-monomer distributions are mainly attributed to the difference within the available active sites within the two catalysts that manifests itself within the rheological and mechanical properties of the polymers also as their melt miscibility. However, polymer density is often controlled by the ethylene/co-monomer molar ratio, temperature, and therefore the catalyst type. The power to crystallize the substance is suffering from its relative molecular mass, concentration of branches, and their distribution along the backbone of the co-polymer. So as to know the crystallization behavior of the branched molecules, more homogeneous fractions of the co-polymer are required. The processing ability and therefore the properties of the ultimate product depend strongly on the branching of the polymer [10,11].

III. RESULTS AND DISCUSSION

In this study, two different catalyst preparation methods namely reaction and recrystallization were developed and compared so as to clarify the correlation between their nature and polymerization behavior. Throughout this article, we have reviewed the changes and current state of PE and PP manufacturing processes, including role and kinds of catalysts and co-catalysts employed over the years. Although Ziegler-Natta catalysts have been used extensively since their discovery, metallocene catalysts and co-catalyst systems have recently been replaced. More laboratory-scale work is usually recommended to know the complexity of the polymerization process, so more information is available for optimization purposes [10].

A. Effect of Temperature

Based on the polymerization temperature for catalyst Ziegler-Natta and metallocene, it is found that the metallocene catalyst exhibited higher activities than Ziegler-Natta catalyst. It was observed that activities increased with increasing the polymerization temperature from 40 °C to 60 °C. However, activities decreased with increasing the temperature to 70 °C. The dependence of polymerization temperature on isotacticity of PP produced from both Ziegler-Natta and metallocene catalysts was also observed [11].

B. Effect of Pressure

It was observed from the Pipatpratanporn's article that metallocene catalysts are much more active than Ziegler-Natta catalysts. The activity of the metallocene catalyst increases almost linearly with increasing propylene pressure, and considering the activity of the Ziegler-Natta catalyst, it shows that the propylene pressure has a weaker effect. Explanation of the different catalytic responses to

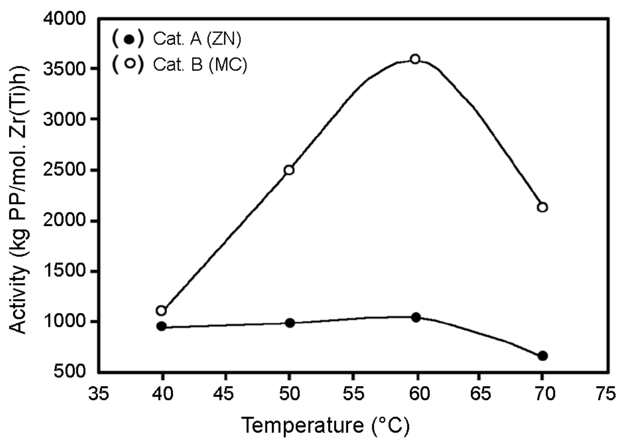
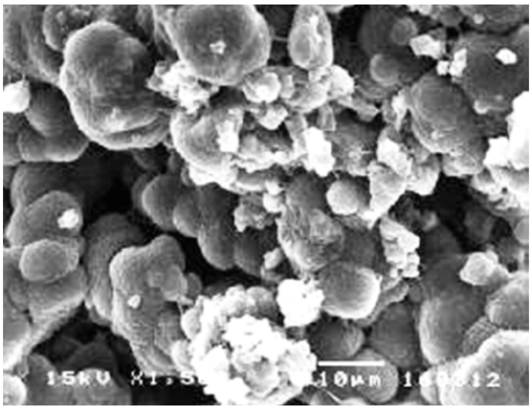
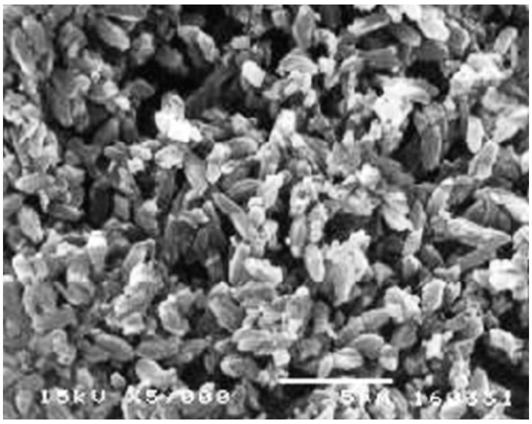


Fig. 4. Effect of polymerization temperature on activities for Ziegler-Natta and metallocene catalysts [10].



(a)



(b)

Fig. 5. (a) Ziegler Natta- based PP and (b) metallocene-based PP.

propylene must lie in the solubility of the propylene in the reaction medium for both catalytic systems [12].

C. Microscopic Structure of Ziegler-Natta and Metallocene-Based PP

T_m of PP produced from the ZN catalyst was high, indicating higher crystallinity. There was no significant change in morphologies (as shown in Figs. 5a and 5b) of PP upon changing the propylene pressures between 40 and 100 psi. It is known that temperature, pressure and also the polymerization time may affect on the fragmentation of heterogeneous catalyst. However, it seems that these effects are pronounced only at a particular level. As reported by Fink group [13] for propylene polymerization, the pressure of 80 bar and temperature of 50 °C were used for 12 h. The activities of the MC catalyst were much higher compared to those of ZN catalysts. However, activities for the MC catalyst essentially decreased when high concentrations of catalyst were used. It is known that at high catalyst concentrations, the coupling reaction of active complex can occur, leading to the catalyst deactivation [14].

IV. CONCLUSION

This paper presents the changes and current status of PE and PP production processes, including the role and types of catalysts and co-catalysts used over the years. Although Ziegler-Natta catalysts have been used extensively since their discovery, they have recently been replaced by metallocene catalysts and co-catalyst systems. We have studied the performance and production mechanism of both PP and PE polymers as well as the prospects for future research [14]. The influence of crystalline properties on the processing ability alongside the mechanical properties of melt spinning fibers are well discussed. Low T_m and high isotacticity of Ziegler/Natta-based PP are some of the advantages that manifest themselves both in terms of fabrication and fiber properties. The newly developed metallocene-based PP is confirmed to be a promising candidate for producing high-performance fibers by the melt spinning process [15].

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