MODELING REINFORCEMENT STRUCTURES IN TEXTILE AIMED AT BIOMECHANICAL PURPOSES

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ABSTRACT

While sporting, muscles, tendons and the body in general come under extreme loads which may lead to wrong movements and injuries which impact the performance or lead to mandatory rest. As athletes often wear compression garments, we investigate how reinforcement structures such as elastic bands, yarns or fabric strips with a given pretension, or rigid structures can be added to compression garments to prevent incorrect sport movements. This paper discusses how an existing simulation tool (DySiFil) can be adapted to be able to extract supportive forces and pressures and validates the findings for the case of overextension of the fingers and the thumb.

Key Words: dynamic yarn simulation, DySiFil, reinforcement band, thumb guard

1. INTRODUCTION

Sport is a healthy activity required for a healthy life. Once people sport however, they often want to explore their limits, and therefore expose their muscles, tendons and the body in general to extreme loads. Each sport is prone to specific injuries. For instance, the literature reports about hand injuries in various sports [1] and rib stress fractures in rowing [2]. Sportwear is adapted to meet sport-specific needs as good as possible and compression garments are often used in many sports to prevent injuries, to help recovery or to enhance performance [3]. This opens the option to adapt the compression garment and include some reinforcement structures, as a comfortable exoskeleton, aiding in the prevention of sports-specific injuries. These reinforcement structures can be elastic bands, yarns or fabric strips with a given pretension, or rigid structures that are laminated, integrated in a brace structure or 3D printed [4, 5, 6] on the fabric.

To aid in the design of these reinforcement structures, it is needed to investigate the influence of the structures on the body movement, in order to determine if they have the desired effect, protecting against incorrect movements. Biomechanical modelling is an option in this as these simulate the movement of the human body under external factors, for example with a tool like OpenSim or ADAMS [7]. These tools however are ideal for rigid braces, but not for compression garments as they can't yet include a clothing layer. Another approach often taken is to look only at the 3D body shape, and model clothing over this, in order to obtain the pressure in that static position [8]. In this manner, correct pressure information can be obtained, but no actual movement is present yet, and localized reinforcement structures have not been considered yet. Finally, body part simulations have been done including bone structure, soft tissue and skin [9]. These models allow for the interaction of the pressure exerted by a compression garment with the underlying skin and muscles. These models require however a

large computational time and reinforcement structures or dynamic movements are not easily added.

Our interest is in simulating a compression garment which is not overly constricted (<10 mmHg) to allow the full range of sport motions needed without any extra energy needed to perform this movement, and add narrow reinforcement structures that hinder unwanted movements. We selected the yarn simulation tool DySiFil (Dynamic Simulation of Filaments) to model the reinforcement structures, and determine their biomechanical effect. DySiFil has been used to simulate weft yarn insertion during airjet weaving as well as yarn splicing [10]. DySiFil does not provide pressure information therefore this has to be added. Pressure is a side effect of the arising tension forces and needs to remain below a given preset value to ensure the compression garment remains comfortable. Next, DySiFil is used to determine the effect of a reinforcement structure on body movements. As use-case we select a system to avoid overextension of the fingers, and look into a thumb guard prototype to protect against a sprained thumb.

2. MATHEMATICAL MODELLING

2.1 DySiFil

We apply numerical modeling to determine the optimal properties and shapes of reinforcement structures attached to compression garments. Full 3D modeling of the fabric would be complex and slow in use. We therefore opt to reduce the fabric to a monofilament along the stretch direction of the fabric, and connect it to filaments representing reinforcement bands or structures in the main direction of deformation. This should allow to simulate the vast majority of possible structures in an efficient way, allowing for iterative prototyping. We apply DySiFil for the modeling, which is a mass-spring based model for monofilaments. We adapt it to allow to extract pressure information, to allow for different filament segments instead of a single long monofilament, and investigate filament-filament interaction.

DySiFil is a mass-spring model of yarns, dividing a yarn in N mass points p_i having speed v_i and mass m_i. Their movement under a force F_i is solved via the forward Euler method. Considering a known solution at time t^n the solution at $t^{n+1}=t^n+dt$ is obtained by solving the resulting system

$$v_i^{n+1}=v_i^n+F_i^n \, dt/m_i$$
$$p_i^{n+1}=p_i^n+v_i^n \, dt \qquad\qquad (1)$$

In this the forces F_i are the summation of the gravity force $F_{g,i}=m_i g$, the bending force, the tension force, the airflow drag force, and friction and clamping forces [11].

2.2 Determining Pressure

For our application, most of the yarns are in contact with a surface (the human body), so handling of the contact forces is of the utmost importance. Using a model for contact based on impulses, the pressure that the compression garment exerts on the body can be obtained. We present the contact procedure that was considered in DySiFil, allowing to correctly include the friction properties during contact. A mass point of our yarn is tracked, and its new position is

computed with (1). For every point, it is determined if it is now *in* a surface. If so, the contact algorithm is triggered for this point.
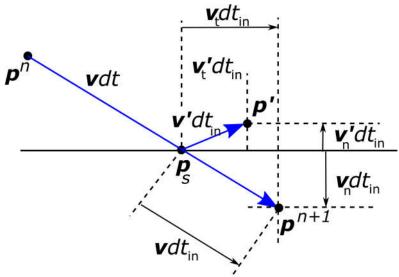

Figure 1. Contact algorithm schematically

Consider this to be the case for a mass point p^n, with computed speed v, arriving at p^{n+1} inside a surface as in Fig. 1. Compute via linear interpolation with the surface the position of contact p_s, then we can compute the time of entry in the surface as $dt_{in}=(p^{n+1}- p_s)/v$. The surface has a collision coefficient β and static and dynamic friction μ_s and μ_d respectively. Set $\beta'= \beta$ if p^n not on the surface, and $\beta'=0$ otherwise as no collision can occur then, and decompose v into its normal and tangential component at the location p_s of the collision, $v= v_n + v_t$. Set the new normal speed as $v'_n=- \beta'v_n$. Compute the normal impulse as $I_n= v'_n-v_n=-(1+ \beta')v_n$. Set the tangential impulse needed to stop the mass point to $I_t^{n+1} = - v_t$. We can determine the actual tangential impulse I_t' lost by considering if friction occurs or not. The particle slips over the surface and loses friction energy if $\| I_t^{n+1} \| > \mu_s \| I_n \|$, in which case $I_t' = \mu_d \| I_n \| (I_t^{n+1} / \|I_t^{n+1} \|)$, while otherwise we set $I_t'=I_t^{n+1}$, as all tangential speed will be lost. With these considerations, we can compute the actual position p' after collision as $v_t' = v_t+I_t'$, $v' = v'_n + v'_t$ and finally $p'=p_s+v' dt_{in}$. This contact procedure was validated by comparing numerical experiments with analytical solutions of collision and gliding of mass points.

With above data, we can derive the pressure P at p_s as

$$P = \frac{m\|I_n\|}{dt_{in}\ W\ L}, \tag{2}$$

where W is the width of the yarn (or strip, or band) represented by this mass point, and L the distance between mass points taking into account the stretch.

2.3 Validation

DySiFil was developed to allow fast simulation of yarn insertion during airjet weaving, while for this application we want to use the results for fabrics that are almost always in contact with a surface with forces pushing the mass nodes into the surface. We validate the approach using the LaPlace law for the relation between wall tension T $(T=F/W)$ and pressure P on an ideal cylinder with radius R, which is $T=P R$. For fabrics or bands, which have no fixed height h, one

determines Young's Modulus times the height, written as *Eh*, and we can derive that the pressure should satisfy

$$P=Eh \, \varepsilon \, / \, R, \qquad\qquad (3)$$

where ε the strain in %. Consider a fabric with *Eh*=900 N/m for a strip of width W=4 mm, and 10% strain, over a cylinder with radius 5 cm, then we should have under that strip a pressure *P*=1.8 kPa. This is modelled with DySiFil, and correct pressures obtained, showing the accuracy of our approach, Fig. 2. This test was performed over a large range of strains and grid sizes. It must be noted that it is required that the yarn segments are larger than the grid of the object discretization over which the yarn is placed, this to avoid regions with zero pressure due to geometry effects.
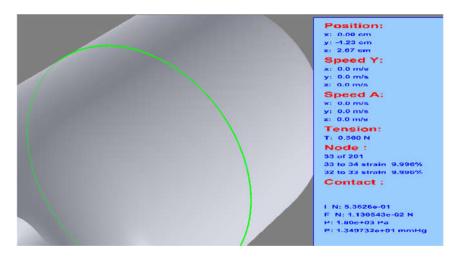

Figure 2. Example DySiFil output testing Laplace Law, 10% strain, pressure 1.8 kPa (13.5 mmHg)

3. EXPERIMENTAL RESULTS

3.1 Overextension Protection

One application is to determine the pressures exerted by an overextension protection running under the fingers. For this, we digitally construct a finger consisting of 2 phalanges and a joint, and bend it, keeping the reinforcement structures anchored to the finger, see Fig. 3. Total simulation time is 10 seconds on an Intel Core i7-4790 CPU@3.6GHz, allowing for fast prototyping of designs.

With the same material as in the previous section, overextension of 30 degrees leads to only a force of 0.37 N overall in the structure. However, at the joint pressure rises to 160 mmHg over a distance of 1 mm. This shows a limitation of our approach. As the bodies used in this simulation are rigid, they do not respond to this pressure. We can assume that the finger would be locally pressed in, distributing the pressure over a larger surface area of the reinforcement structure. In this case, assuming the skin becomes slightly pressed in over 5 mm, the pressure will decrease to around 32 mmHg.

We can conclude that the model is able to simulate the effects of reinforcement bands added in textiles in a dynamical fashion, by placing the bands as desired over representations of the human body.
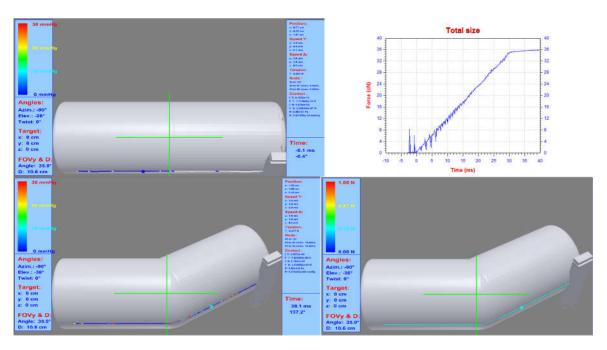

Figure 3. Overextension of a finger, resembling proximal and intermediate phalanges. Top: Start position (Left) and dynamical simulation buildup of tension force in the band (Right). Bottom: Final result: pressure data up to 160 mmHg at the joint (Left) and tension data over the strip almost everywhere around 0.36 N (Right)

3.2 Thumb Guard

The developed numerical model cannot be applied yet to simulate a structure where part of the structure connects between body parts. An example of this is a thumb guard prototype as given in Fig. 4, where a fabric strip is added between two bands, one around the base of the thumb, and one around the metacarpal bones of the hand. This is a structure added to a compression glove to avoid a sprained thumb. For this, the simulation tool must be further developed, as the connecting band needs to pull on the other two bands, which requires band-to-band interaction, and not only band-body interaction as in Section 3.1.

Figure 4. Example prototype for a thumb guard. Two compressive elastic bands (blue) are connected by a non-elastic thumb guard band (red)

4. CONCLUSION

DySiFil was adapted to allow the extraction of pressure data exerted by bands, allowing to simulate in a dynamic fashion the movement of a human body part (i.e., finger or thumb) and the effect of this movement on reinforcements integrated into clothes (e.g. glove). Friction band-body was included allowing sliding of the band. Good results were obtained, though as body parts in DySiFil are rigid, the resulting pressure should be averaged over a larger zone.

At the moment the simulation is restricted to bands layered in compression garments worn over one body parts (i.e., finger). Band-to-band interaction must be added to allow simulation of more complex compression structures that connect between body parts.

5. ACKNOWLEDGEMENTS

6. REFERENCES

1. Gaston G.R, Loeffler B.J, Sports-specific injuries of the hand and wrist, *Clin Sports Med*, 2015, Vol.34, 1-10
2. Warden S.J et al, Aetiology of rib stress fractures in rowers, *Sports Med*, 2002, Vol.32, No.13, 819-836
3. Engel F, Sperlich B, *Compression Garments in Sports: Athletic Performance and Recovery*, Springer International publishing, Switzerland, 2016.
4. Cole A.K et al, Scapular Bracing and Alteration of Posture and Muscle Activity in Overhead Athletes With Poor Posture, J Athl Train, 2013, Vol.48, No.1, 12-24
5. Reynders, D, *3D Printing: Adhesion to Textile Substrates*, master thesis UGent, Gent, 2016.
6. Harte D, Paterson A, The fastest field sport in the world: A case report on a 3-dimensional printed hurling gloves to help prevent injury, *J Hand Ther*, 2018, Vol.31, No.3, 398-410
7. Tarnita D et al, Numerical Simulations and Experimental Human Gait Analysis Using Wearable Sensors, Husty M and Hofbaur M (eds.), New Trends in Medical and Service Robots, *Mechanisms and Machine Science*, Vol. 48, Springer, 289--304
8. Liu K et al, Development of upper cycling clothes using 3D to 2D flattening technology and evaluation of dynamic wear comfort from the aspect of clothing pressure, *International Journal of clothing science and technology*, 2016, Vol.28, No.6, 736-749
9. Rohan C.P-Y et al, Biomechanical response of varicose veins to elastic compression: A numerical study, *Journal of Biomechanics*, 2013, Vol.46, 599–603
10. De Meulemeester S, Puissant P and Van Langenhove L, Yarn simulations with sharp edges, *Textile Research Journal*, 2011, Vol.81, No.7, 714-729
11. De Meulemeester S, Puissant P and Van Langenhove L, Three-dimensional Simulation of the Dynamic Yarn Behavior on Air-jet Looms, *Textile Research Journal*, 2009, Vol.79, No.18, 1706-1714.