Short communication

Proof-of-concept for a segmented composite diving suit offering depth-independent thermal protection

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Abstract

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Heat loss is a major health hazard for divers. It can lead to hypothermia, organ damage, unconsciousness, and eventually death. Hence, thermal protection is essential for diver safety. Typically, protection is provided by wetsuits made of bubbled neoprene. However, neoprene shrinks with depth and loses thermal insulation capability, while thick neoprene suits make swimming exhausting. Herein, a proof-of-concept is presented for a solution to both problems: a 'K-suit' made of thermally-resistive composite segments attached to a thin neoprene suit. The segments are made of hollow glass microspheres embedded in carrier polymer thermally cured in 3D-printed molds based on 3D-scans of the diver's body. The K-suit was compared in field trials with a 7 mm commercial neoprene suit by diving in pairs, while automated dataloggers registered pressure and temperature inside and outside both suits. The K-suit demonstrated +4ºC higher temperature difference than the 7 mm neoprene. Also, divers reported that the K-suit had the ergonomics of a 3 mm neoprene suit. These preliminary results represent a proof-of-concept for the K-suit and promise further improvements with potential impact on diver safety.

Introduction

Diving is a potentially dangerous undertaking for humans. Heat loss is one of its major hazards. Compared to air, sea water has ~24x greater thermal conductivity and ~4x greater specific heat capacity.[1] As a result, even well-adapted sea mammals lose heat to ambient water up to 4.5x faster than in air at the same temperature difference.[2] That heat loss[3] means hypothermia[4] occurs far more rapidly in submerged humans.[5] As the diver's core temperature declines, the diver runs the risk of organ damage, loss of consciousness and eventually death. It takes ~1 h in 10°C water or ~15 min in 5°C water for an unprotected lean human to reach hypothermia.[6] Even extensively trained and conditioned divers cannot compensate for the heat loss.[7] Hence thermal protection is critical, particularly in longer dives and in cold waters.

The typical thermal protection is a wetsuit comprised of neoprene (3–8 mm in thickness) encased between two thin layers of cloth (0.5–1 mm thick). During fabrication, the neoprene is 'bubbled' with air or nitrogen to form microscopic pockets, which provide the thermal insulation and mechanical flexibility to the suit. Protected by a neoprene wetsuit, a lean diver in 5°C water would reach hypothermia in ~1 h in a 3 mm suit and in ~1.5 h in a 5 mm suit.[6] Thicker suits offer more protection but are less flexible, constrain ranges of motion and fatigue the diver faster. Consequently, current suits do not exceed 8 mm in thickness. Furthermore, the air bubbles in the neoprene are easily compressible, so the insulation is reduced as depth and ambient pressure increase.[8] For example, neoprene loses ~50% of its thermal protection at 30 metres of seawater (msw).[9]

We developed a composite material made of hard hollow microspheres embedded in carrier polymer.[9] We experimentally showed that the composite offers more thermal protection than bubbled neoprene and also retains its thermal protection at depth.[9]

However, the composite is less flexible than neoprene, and so cannot be tailored like cloth. Instead, we built a segmented suit (the 'K-suit'), wherein monolithic plates of the composite material cover body areas that do not bend, while areas of significant bending are left to thin neoprene. In this proof-of-concept study, we briefly describe the design and fabrication process, and present preliminary results of field tests to show proof-of-concept.

Figure 1
Suit design and fabrication; the diver's 3D body scans (A) were ergonomically segmented (B) and converted into mold designs (C, D). The molds were 3D-printed in polycarbonate and used to cast composite segments (E). The segments were fitted (F, G) to the diver, trimmed, and sealed in external pockets on a 3 mm neoprene suit, to produce the K-suit (H)

Table 1
Biometric data for the paired divers; BMI – body mass index

Divers	Age (years)	Height (m)	Weight (kg)	BMI $kg \cdot m^{-2}$
K-suit	28	1.68	77	27.4
7mm neoprene	34	1.83	111	33.2

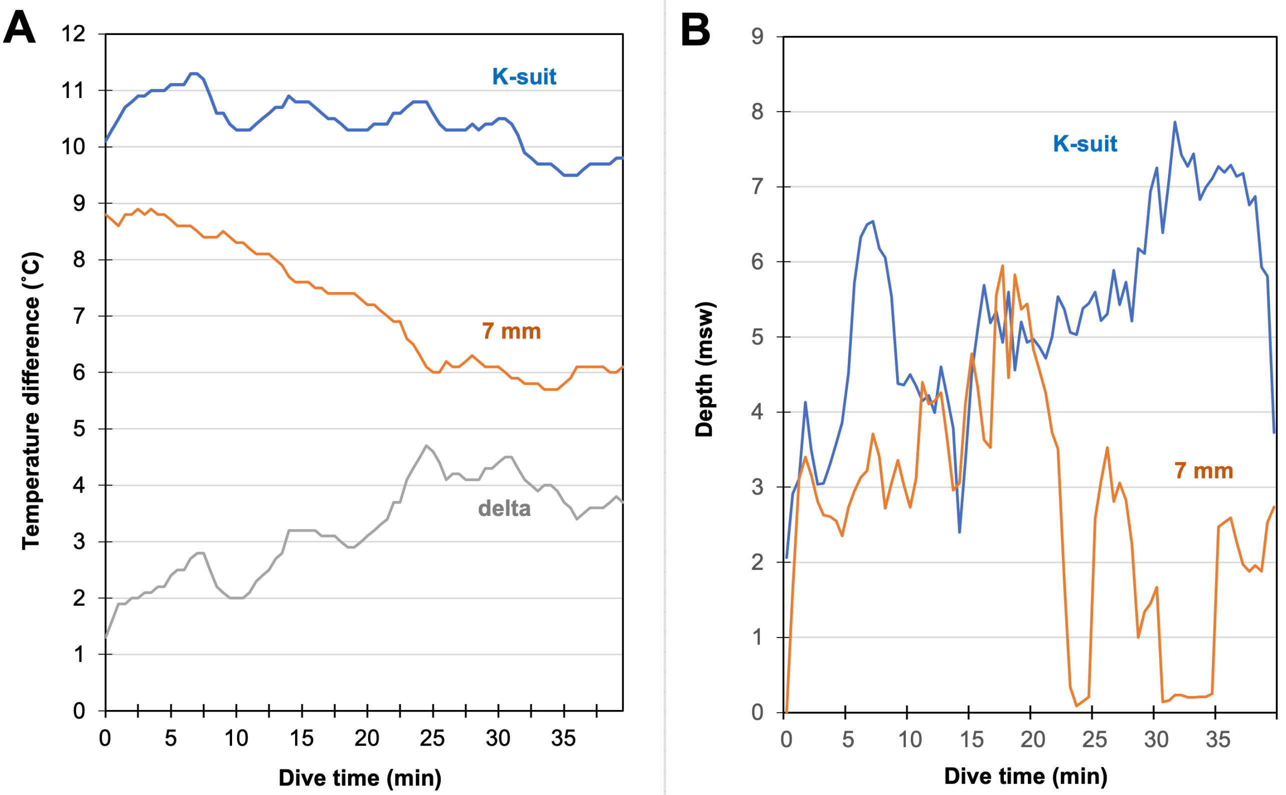
Methods

Field test plans were reviewed and approved by the Institutional Review Board (IRB) at the Naval Postgraduate School (NPS).

Three-dimensional (3D) body scans (Figure 1A) of divers wearing thin neoprene suits were generated by a portable scanner attached to an iPad. The scans were smoothed, simplified, converted to stereolithography (STL) format in MeshLab (Figure 1B) and converted into 3D mold designs in SolidWorks (Figure 1C, D). The designs were 3D-printed in polycarbonate at half-density mesh on a Fortus 400mc 3D printer (Stratasys, Eden Prairie, MN, USA). Sylgard 184 (Dow Corning, Midland, MI, USA) prepolymer was mixed with K1 hollow glass microspheres (3M, Saint Paul, MN, USA) in a planetary mixer (ARE310, THINKY, Japan) for 4 min at 1500 rpm, and cured in the molds in a VWR forced air oven (Avantor, Radnor, PA, USA) at 80°C for 2 h. The casts were extracted, trimmed, and fitted and traced onto a 3 mm suit worn by the diver (Figure 1E, F, G). Thin neoprene pieces were cut to match the tracings and glued to the suit using neoprene cement, thereby encapsulating the composite segments and attaching them to the 3 mm suit in watertight external pockets. This completed the assembly of the K-suit.

Preliminary field tests were conducted by a pair of divers in Monterey Bay, wherein one diver wore the K-suit and the other a commercial 7 mm neoprene suit (AquaLung, Vista, CA, USA). Both were trained US Navy divers and Naval Postgraduate School students, with muscular builds and in excellent physical shape and health. Biometric data for the two divers are shown in Table 1.

Figure 2
Field test results; the K-suit wearer (blue datapoints) dived with a buddy wearing a commercial 7 mm neoprene suit (orange datapoints) in salt water in Monterey Bay at ~10°C. Both divers wore automated dataloggers inside and outside the suits, recording temperature and pressure. The temperature delta between the inside and outside for each diver, and the difference between the two deltas (grey datapoints) (A) and the corresponding depths (B) are plotted against time since the start of the dive



The temperature of the salt water was ~10°C and the diving depth was up to 10 msw. Pressure and temperature were recorded by OM-CP-PRTEMP1000 automated dataloggers (Omega Engineering, Norwalk, CT, USA). Each diver wore one logger between his suit and his breastbone, and one on the outside attached to his buoyancy control device. Loggers digitally recorded temperature and pressure at 0.1 s intervals. After the dive, the watertight caps on the loggers were unscrewed to access the USB ports and the data were downloaded.

Results

Figure 2 shows the field test results. Figure 2A shows the temperature difference (inside minus outside) for each diver over time since the start of the dive. Figure 2B shows the depth of each diver as calculated from the pressure data. The time start is at the beginning of the dive.

These data suggest that the standard 7 mm neoprene suit leads to a quicker drop of temperature difference compared to the K-suit. The results also show that the K-suit maintains about +4°C higher temperature difference compared to the 7 mm suit, as indicated by the delta of the differences on the same plot.

In terms of ergonomics, the K-suit wearer felt that the K-suit had the same ease of movement as a 3 mm neoprene suit, i.e., a significant improvement compared to a 7 mm suit. On the other hand, added difficulty was experienced in donning and doffing the K-suit.

Discussion

Figure 2B reveals the neoprene wearer spent more time at shallower depth than the K-suit wearer. It is known that neoprene insulation worsens with depth.[9] In addition, the K-suit wearer was shorter, lighter, and with lower BMI than the neoprene wearer (see Table 1). Therefore, he had a higher surface-to-volume ratio and lower thermal capacity, and was at a disadvantage in thermal performance. These observations suggest the K-suit thermal advantage may be larger than Figure 2A suggests, but definitive conclusions would require a proper study with a larger number of subjects. Indeed, while these preliminary results represent a proof-of-concept, more subjects and dives would allow appropriate statistical analysis. The physical differences between divers would be better accounted for by alternating the wearing of the K-suit and neoprene.

The added donning/doffing difficulty of the K-suit is chiefly attributed to design that is yet to be perfected. For example, the inclusion of pleated cuffs with zippers on the wrists and ankles ought to help solve the problem satisfactorily. Similar pleating can be included in other areas as needed. Ergonomics improvements must be studied quantitatively.

Future work would complete the K-suit's composite coverage by adding segments for the head, upper arms, and lower arms, and then field testing with analogous methodology. Diving longer, at greater depths and in colder waters would quantify any advantage in colder environments. The loggers would be replaced with thermistors at multiple sites on the skin of the divers.

Conclusions

We have presented a novel segmented composite diving suit called the 'K-suit'. A single, preliminary field test suggested the K-suit outperforms a commercial 7 mm neoprene suit in both thermal protection and ergonomics. Hence, the K-suit has high potential practical utility and promise. The thermal and ergonomics superiority of the K-suit, combined with its relatively easy and inexpensive manufacture, could be of great practical utility to the military, professional and recreational diver communities, but definitive conclusions require further study.

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