安全性

各関節の角度とモーター出力はソフトウェアにより監視されており、これらが事前に設定した範囲を超えた場合には、自動的に安全範囲内になるように制御される。

緊急停止スイッチについては、装着者と付添人それぞれが押すことができるよう２つ用意される。緊急停止時およびその他の理由により電源供給が途絶えた場合は、急な脱力により装着者に大きな負荷がかからないよう、肘関節のブレーキと指部分のギアの摩擦力によって、すべての関節がその位置で固定される。

また、関節と逆方向に力がかかり続ける状態になった場合、装置を身体に装着するために使用される機構が外れるよう構成されている。

C. 研究結果（BOTAS 制御系の改良）

これまで、高周波の視覚刺激により誘発される SSVEP を利用したアシストスーツ駆動実験において、健常者 4 名による検証では、平均して 3～5 秒程度で SSVEP が誘発されてくることが確認された（図２）。さらに、実際にアシストスーツによって運動を補助された状態でボールを運ぶ課題を実施した結果、80～90%の高い精度で目的位置まで到達運動に成功した（図３）。このように、高周波帯域の視覚刺激を用いた条件においても、低周波帯域の条件と同等のパフォーマンスを示すことが確認され、より装着者が使いやすいシステムの構築に成功した。

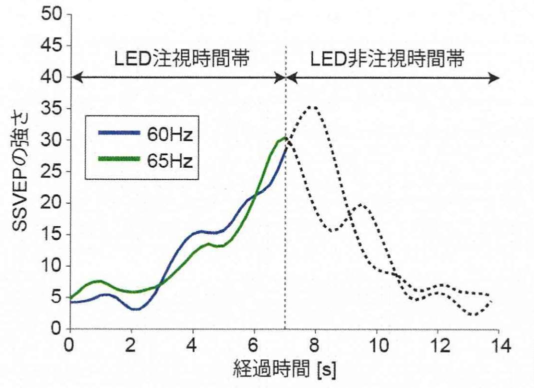

図 2: 高周波点滅刺激により誘発される SSVEP

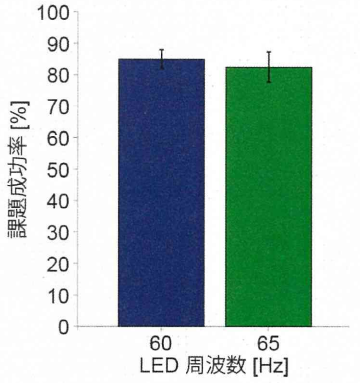

図 3: ボール運び課題成功率

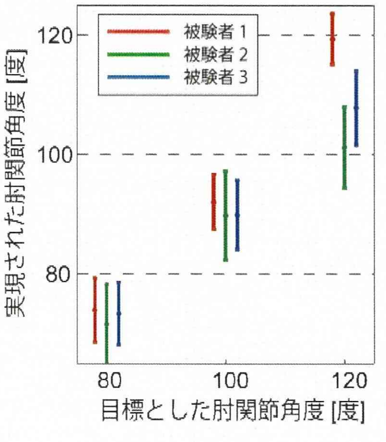

図 4: 表面筋電位により駆動された BOTAS の関節角度

また表面筋電位を使った駆動システムについては、健常者 3 名による検証実験を行った。その結果、各被験者は表面筋電位を用いたアシストを受けながら、肘の角度を目標角度に合わせることができた（目標角度と実現角度の相関：0.92±0.052）（図４）。

D. 考察

アシストスーツ制御用に利用する脳波（SSVEP）を誘発するための視覚刺激を高周波帯域とすることで、装着者が刺激のちらつきを知覚することなく利用することが可能となった。これにより、将来アシストスーツによるリハビリテーション訓練を行う場合にも、比較的長時間利用しやすくなったといえる。

また本年度開発した表面筋電位による駆動システムにより、アシストスーツを装着者自身の行う運動に追従させながら、装着者の力を、物をつかんで運ぶのに十分な程度にまで増強することができる。これにより、表面筋電位が計測可能な患者の運動意図を反映する多様な動作のアシストが実現可能となり、表面筋電位の計測ができない患者にも適用できるこれまでの脳波利用システムと併用することで、より多様な病態への対応が広がるものと考えられる。

さらに、従来BOTASの大きな駆動力供給ボックスによる持ち運びの困難さが課題であったが、新たに開発した軽量アシストスーツBRENDAでは、駆動力を供給する部分すべてを、使用者が装着する部分に組み込むことができた。これにより、麻痺患者の上肢を使った日常生活動作を、麻痺患者自身の運動意図に基づいてアシストすることが可能となると思われる。

今後、BMI技術を用いた装着者の運動意図を反映したシステムが、どの程度リハビリテーションとして効果的な手法となりえるか、基礎的な検証も併せて進めていきたい。

分担研究課分担研究課題（小課題）：BMIの最適化に向けた研究

A. 研究目的

脳からの信号を計測し、それを利用して機器操作を行う「ブレイン-マシン・インターフェイス（Brain-Machine Interface: BMI）」の技術の研究開発を行う際に、脳機能の作動原理に関する情報を用いることで、システムのさらなる最適化が可能となる。また、その作動原理となっている神経基盤を対象としたトレーニングを行なうことによって、さらなる性能向上が期待される。

本分担研究では特に、将来的なニューロフィードバック・トレーニングの導入を考慮した、リアルタイム解析のための系の高度化を目的とする。具体的には、脳の皮質内の電流を推定する技術を用いることによって、これまでセンサーレベルだったために存在した、(1)マルチセッションで頭部位置が変化し、それに伴い信号が変化する問題、(2)複数被験者の合わせ込み（レジストレーション）の方法の欠如の問題が解決する（図1）。さらに、複数の脳領域間の機能的結合をフィードバックすることを可能とした。

B. 研究方法

リアルタイムMEGを用いたBMI系の高度化を行う。系の構成を図2に示す。昨年度開発したリアルタイムMEGでは、フィードバックされるのは、センサー毎の信号であったが、今年度ビームフォーマーという信号位置特定技術をリアルタイムMEGに実装することで、脳内位置に基づいた信号をフィードバックできるようになった（Ora et al., *submitted*）。また、機能的結合の推定にはimaginary coherenceという結合度指標を用いた。MEGで一般的に用いられているノイズ除去技術や本研究で用いている信号位置特定技術を用いると、複数の脳領域の電流推定結果に偽の相関が混入し得るがimaginary coherenceを用いることで、その様な偽の相関を取り除くことができる。また、神経伝達に基づく脳領域間の真の相関は取り除かれずに残ることが期待される。処理の流れを図3に示す。実験では、明滅する視覚刺激（フリッカー刺激）に注意を注ぐという、SSVEPを用いたBMIにおいて行なわれる認知課題

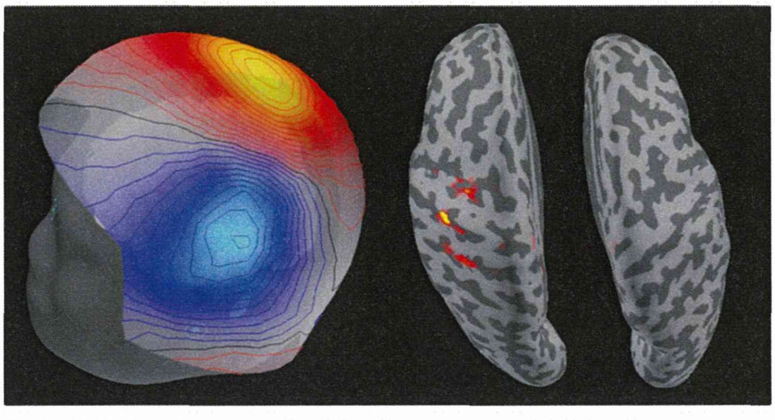

図1センサーレベル信号（左）と皮質内電流推定（右）のイメージ

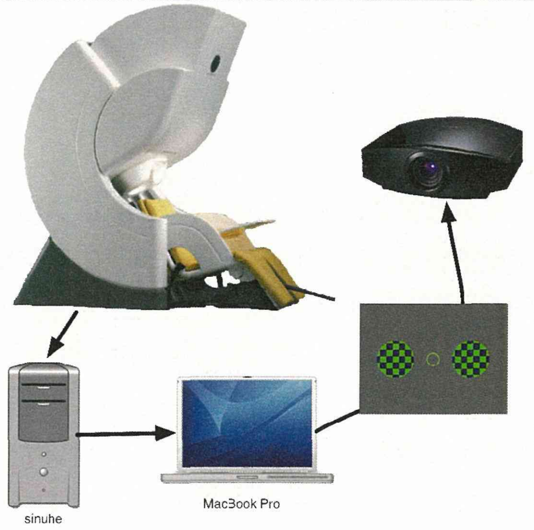

図 2 系の構成

を行ない、その際の脳内の機能的結合をフィードバックし、実験後解析にて機能的結合の変化を評価した。

C. 研究結果

リアルタイム MEG を用いた BMI 系の高度化を行った。検証実験(n=1)において、被験者は右にあるフリッカー刺激に注意すると、左視覚野と右後部頭頂皮質との imaginary coherence が右視覚野と右後部頭頂皮質との imaginary coherence よりも強くなり($T_{39}=2.52, p=0.0158$)、また、左 V5 領域と右後部頭頂皮質との imaginary coherence が右 V5 領域と右後部頭頂皮質との imaginary coherence よりも強くなった($T_{39}=3.21$, $p=0.0026$)。被験者数は 1 であるが、これらの結果は、Buchel ら(1997)と一貫している。

D. 考察

本小課題では、MEG のリアルタイム解析系を高度化することにより、より効率的な BMI に向けた研究開発を行った。センサーレベル信号ではなく、特定の解剖学的位置にある皮質内の電流を推定しフィードバックする、MEG のリアルタイム解析系を構築したことで、より効率的に脳の可塑性を誘発する系の構築が可能となると考えられる。

今後はこれらの結果を組込むことで、現在より効率的で使いやすい BMI 機器の開発を進めていきたい。

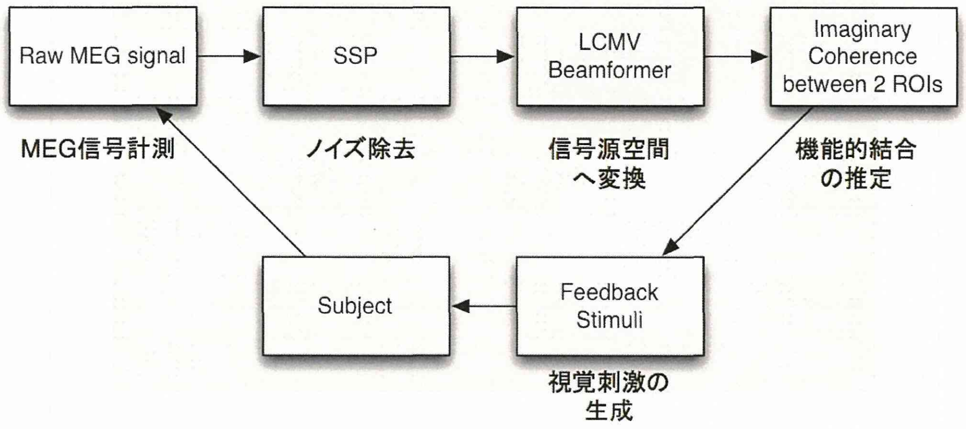

図 3 MEG ニューロフィードバック系の概念図

厚生労働科学研究費補助金（活動領域拡張医療機器開発研究事業）
分担研究報告書（平成２２年度および平成２４年度現在まで）

ブレイン—マシン・インターフェイス（BMI）による障害者自立支援機器の開発に関する研究

分担研究課題名　ロボットスーツ HAL の障害者自立支援機器への展開に関する研究

分担研究者　山海　嘉之　筑波大学大学院システム情報工学研究科教授

研究要旨

本研究は、活動領域拡張医療機器開発事業として、ブレイン—マシン・インターフェイス（BMI）による障害者自立支援機器の開発に関して、研究を推進するものである。BMI に関しては、非侵襲型のインタフェースを用いることとし、また、障害者自立支援機器として、これまで研究開発を進めてきたロボットスーツ HAL を改良・活用する。本年度は、従来装置を改良することによって、下肢用試験システムの開発推進、ならびに、上肢用試験システム、把持動作支援用のハンド・フィンガー部を準備し、実験を行った。

A. 研究目的

本研究では、活動領域拡張医療機器開発事業として、ブレイン—マシン・インターフェイス（BMI）による障害者自立支援機器の開発に関して、研究を推進することを目的としている。

従来装置を改良することによって、下肢用試験システムの開発推進、ならびに、上肢用試験システム、把持動作支援用のハンド・フィンガー部を準備し、基礎的実験を行う。

B. 研究方法

現状の BMI 技術による分解能を検討すると、侵襲型であっても非侵襲型であっても高い分解能を期待する事は現時点では困難であるため、検討の結果、本研究では非侵襲型の適用が当面は妥当であると判断し、これを想定して研究を進めている。また、運動機能障害者の自立支援機器として、これまで研究開発を進めてきたロボットスーツ HAL を改良・活用することで研究推進の効率化をはかり、改良型試験装置の製作と基礎実験を行う。

（倫理面への配慮）

人支援技術の研究開発の推進には、被験者に対する適切な対応が求められるため、当該研究では、厚生労働省の臨床研究に関する倫理指針を遵守した。

C. 研究結果

研究開発方針に従って、従来から研究開発を進めてきた下肢用試験システムの開発推進、ならびに、上肢用試験システム、把持動作支援用のハンド・フィンガー部を当該研究開発推進のために改良を行い（機構的／電子的／制御論的機能の拡充）、動作試験等の実験を継続している。

従来より開発を進めてきた装着型サイバニックハンド・フィンガーに改良を加え（図１）、さらなる小型軽量化や制御精度向上を目指し、現在改良試作および動作検証を進めている。準備を進めている上肢と接合すべく改良を加えている。

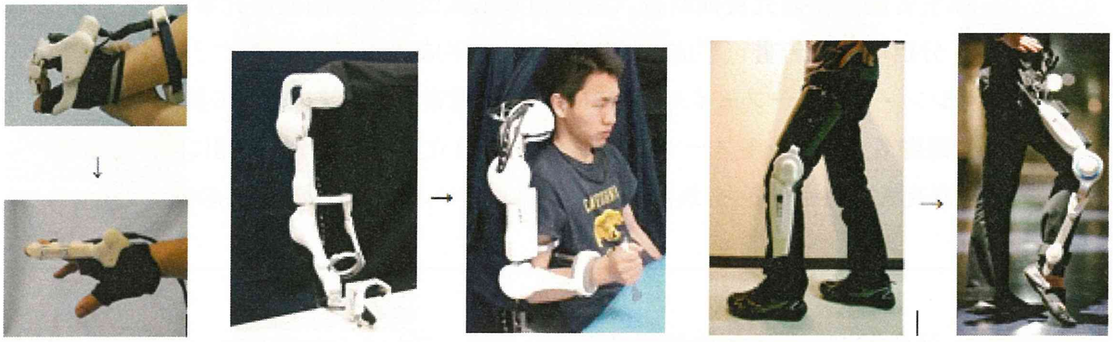

図1　装着型サイバニックハンド･フィンガー、上肢用 HAL、単関節下肢用 HAL（改良版）

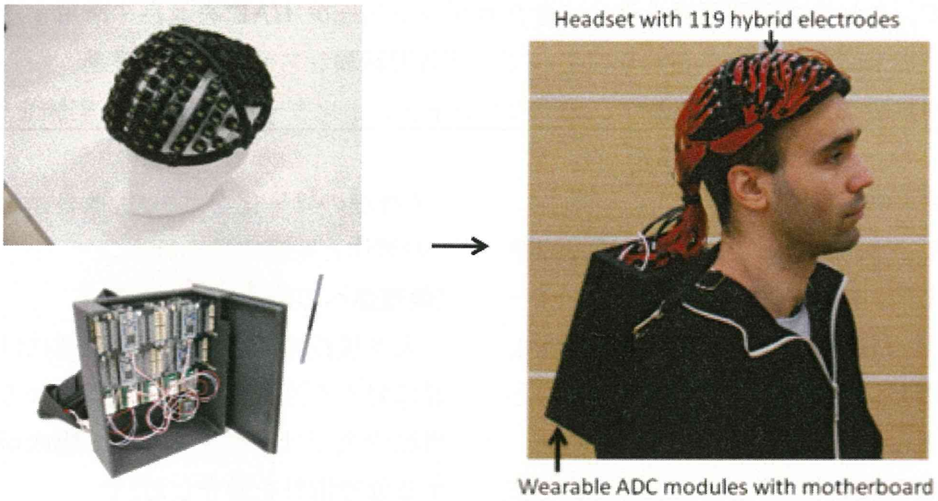

図2　新開発 BMI ヘッドセットとコントロールボックス

また、従来より開発を進めてきた上肢用 HAL についても図１に示すような改良を加え、動作検証を実施中である。

さらに、単関節下肢用 HAL のインタフェース部に対して、BMI との連動が可能となるよう、機構的／電子的／制御論的機能の改良を行っている。更に、BMI に関しても可能な範囲で試行を実施した。図２に示すハイブリッド電極による BMI ヘッドセットコントロールボックスの試作品を制作した。システム全体を組み上げてゆく過程で、要素技術が機能していることを確認するために、簡単なシステムを構成し、脳活動パターンの信号を用いて基礎実験を試みてい

る。

D. 考察

各要素の技術的な改良を行なうことができた。システム全体については、現在、全体の動作検証を進めている。別途インタフェースユニットを構成することも検討する。

E. 結論

当該研究推進のため、機構的／電子的／制御論的機能を自律システムとして適用できるよう要素技術の研究開発を進めることができた。

F. 健康危険情報

該当なし

G. 研究発表

(関連研究の成果を含む)

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H. 知的財産権の出願・登録状況

（これまでの関連研究の成果も含む）

１．特許取得

発明者 山海嘉之
発明の名称 装着式動作補助装置
出願人 筑波大学
出願番号 2012-037595

発明者 山海嘉之
発明の名称 表示装置型リハビリテーション支援装置及びリハビリテーション支援装置の制御方法
出願人 筑波大学
出願番号 2012-040049

発明者 山海嘉之
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発明者 山海嘉之
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出願人 筑波大学
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発明者 山海嘉之、林知広
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出願人 筑波大学、CYBERDYNE株式会社
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発明者 山海嘉之
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出　願　人 筑波大学
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発　明　者 山海嘉之
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出　願　人筑波大学、CYBERDYNE株式会社
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2．実用新案登録

該当無し。

3．その他

該当無し。

III.　研究成果の刊行に関する一覧表

研究成果の刊行に関する一覧表

書籍

著者氏名	論文タイトル名	書籍全体の編集者名	書　籍　名	出版社名	出版地	出版年	ページ
神作憲司	神経難病の生活を支援する BMI	江藤文夫 中馬孝容 葛原茂樹	「CLINICAL REHABILITATION」別冊: 神経難病疾患のリハビリテーション-ケーススタディーを通して学ぶ	医歯薬出版	東京	2012	31-37
神作憲司	脳神経科学と法 Comment1 ブレイン・リーディング	樋口範雄	「Jurist」増刊: ケース・スタディ　生命倫理と法	有斐閣	東京	2012	319-322
神作憲司	脳波で操作する環境制御システムの開発		次世代ヒューマンインタフェース開発の最前線	エヌ・ティー・エス	東京	(印刷中)	

雑誌

発表者氏名	論文タイトル名	発表誌名	巻号	ページ	出版年
Ikegami, S., Takano, K., Wada, M., Saeki, N., Kansaku, K.	Effect of the green/blue flicker matrix for P300-based brain-computer interface: an EEG-fMRI study	Frontiers in Neurology	3	113	2012
Toyama, S., Takano, K., Kansaku, K.	A nonadhesive solid-gel electrode for a non-invasive brain–machine interface	Frontiers in Neurology	3	114	2012
神作憲司	BMI による障害者自立支援	リハビリテーション医学	49(10)	704-709	2012
神作憲司	ブレインーマシン・インターフェイス（BMI）による環境制御	医学のあゆみ			(印刷中)
神作憲司	脳波による実用的な BMI 研究開発	認知神経科学			(印刷中)
武富　卓三, 山海　嘉之,	ロボットスーツ HAL による脳性麻痺患者の歩行支援に関する研究	生体医工学	50(1)	105-110	2012
林　知広, 岩月　幸一, 長谷川　真人, 田上　未来, 山海　嘉之	自力運動困難な麻痺患者に対するロボットスーツを用いた新しい随意運動訓練—重度脊髄損傷患者への臨床適用—	生体医工学	50(1)	117-123	2012
佐邊綾太郎, 林知広, 山海嘉之	視覚情報提示による手すりへの依存荷重フィードバックシステムの開発	日本機械学会論文集(C編)	78(792)	3000-3012	2012

Ianov A.I., Kawamoto H., Sankai Y.	Development of Hybrid Resistive-Capacitive Electrodes for Electroencephalogram and Electrooculogram	IEEJ Transactions of Sensors and Micromachines	133(3)		（in press）
鍋嶌厚太, 河本浩明, 山海嘉之	装着型歩行補助ロボットのリスク分析と安全性試験法	日本ロボット学会誌	30(7-8)	752-758	2012
Yamawaki K., Ariyasu R., Kubota S., Kawamoto H., Nakata Y., Kamibayashi K., Sankai Y., Eguchi K., Ochiai N.	Application of Robot Suit HAL to Gait Rehabilitationof Stroke Patients: A Case Study	Lecture Notes in Computer Science	7383	184-187	2012
山海嘉之, 桜井尊	福祉ロボットにおけるテレロボティクス	日本ロボット学会誌	30(6)	595-598	2012
山海嘉之, 桜井尊	サイバニクスを駆使したHAL(Hybrid Assistive Limbs)最前線	分子脳血管病	11(3)	25-24	2012

IV.　研究成果の刊行物・別刷

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A non-adhesive solid-gel electrode for a non-invasive brain–machine interface

Shigeru Toyama[1]*, **Kouji Takano**[2] **and Kenji Kansaku**[2]*

[1] *Biotechnological Rehabilitation Section, Department of Rehabilitation Engineering, Research Institute of National Rehabilitation Center for Persons with Disabilities, Tokorozawa, Japan*

[2] *Systems Neuroscience Section, Department of Rehabilitation for Brain Functions, Research Institute of National Rehabilitation Center for Persons with Disabilities, Tokorozawa, Japan*

Edited by:
Emanuel Donchin, University of South Florida, USA

Reviewed by:
Eric W. Sellers, East Tennessee State University, USA
Christopher Leroy Frewin, University of South Florida, USA

***Correspondence:**
Shigeru Toyama, Biotechnological Rehabilitation Section, Department of Rehabilitation Engineering, Research Institute of National Rehabilitation Center for Persons with Disabilities, 4-1 Namiki, Tokorozawa, Saitama 359-8555, Japan.
e-mail: toyama-shigeru@rehab.go.jp;
Kenji Kansaku, Systems Neuroscience Section, Department of Rehabilitation for Brain Functions, Research Institute of National Rehabilitation Center for Persons with Disabilities, 4-1 Namiki, Tokorozawa, Saitama 359-8555, Japan.
e-mail: kansaku-kenji@rehab.go.jp

A non-invasive brain–machine interface (BMI) or brain–computer interface is a technology for helping individuals with disabilities and utilizes neurophysiological signals from the brain to control external machines or computers without requiring surgery. However, when applying electroencephalography (EEG) methodology, users must place EEG electrodes on the scalp each time, and the development of easy-to-use electrodes for clinical use is required. In this study, we developed a conductive non-adhesive solid-gel electrode for practical non-invasive BMIs. We performed basic material testing, including examining the volume resistivity, viscoelasticity, and moisture-retention properties of the solid-gel. Then, we compared the performance of the solid-gel, a conventional paste, and an in-house metal-pin-based electrode using impedance measurements and P300-BMI testing. The solid-gel was observed to be conductive (volume resistivity 13.2 Ωcm) and soft (complex modulus 105.4 kPa), and it remained wet for a prolonged period (>10 h) in a dry environment. Impedance measurements revealed that the impedance of the solid-gel-based and conventional paste-based electrodes was superior to that of the pin-based electrode. The EEG measurement suggested that the signals obtained with the solid-gel electrode were comparable to those with the conventional paste-based electrode. Moreover, the P300-BMI study suggested that systems using the solid-gel or pin-based electrodes were effective. One of the advantages of the solid-gel is that it does not require cleaning after use, whereas the conventional paste adheres to the hair, which requires washing. Furthermore, the solid-gel electrode was not painful compared with a metal-pin electrode. Taken together, the results suggest that the solid-gel electrode worked well for practical BMIs and could be useful for bedridden patients such as those with amyotrophic lateral sclerosis.

Keywords: EEG, BMI, BCI, non-adhesive conductive solid-gel

INTRODUCTION

The brain–machine interface (BMI) or brain–computer interface (BCI) is a state-of-the art technology that utilizes neurophysiological signals from the brain to control external machines or computers (Wolpaw and McFarland, 2004; Pfurtscheller et al., 2006; Birbaumer and Cohen, 2007). Much effort has been made to help individuals with physical disabilities such as amyotrophic lateral sclerosis (ALS), stroke, or upper cervical spinal cord injury. Non-invasive BMI does not require surgery. Some non-invasive BMI systems make use of hemodynamic signals using functional magnetic resonance imaging (fMRI; Sitaram et al., 2011) or near-infrared spectroscopy (NIRS; Sitaram et al., 2007; Cui et al., 2010), but the majority of papers report methods using electroencephalography (EEG) signals. The P300 speller, a popular BMI system, uses elicited P300 responses to target stimuli placed among row and column flashes (Farwell and Donchin, 1988). We also used EEG signals in a BMI system that enables environmental control and communication using the P300 paradigm (Takano et al., 2009, 2011; Kansaku et al., 2010). Recent studies have evaluated the use of systems relying on these sensory evoked signals of patients with ALS and other diseases (Piccione et al., 2006; Sellers and Donchin, 2006; Ikegami et al., 2011).

Based on BMI studies, it is possible to build an intelligent house in which home electronics or communication tools such as e-mail can be operated with brain waves (Kansaku, 2011). Therefore, we have conducted measurement tests in patient's homes and in hospitals. However, we felt that the conventional paste-based electrode systems are somewhat awkward to use in practical circumstances (here we use "paste" to mean the conventional paste or gel used for an EEG electrode).

Typical EEG-based BMI electrodes use sticky conductive paste to reduce the impedance between the scalp and electrodes. To use electrodes with paste requires elaborate work not only for preparation but also for removal of the paste. In the preparation stage, paste is first placed on cup electrodes, and then the electrodes are fixed on the head. After using a BMI system, the patient's head must often be washed to remove the dried paste, which adheres tightly to hair. Similar comments are sometimes found in the literature, and some authors have proposed the use of dry electrodes for BMI to avoid tedious preparation and after treatment (Popescu et al., 2007; Liao et al., 2011; Zander et al., 2011). Popescu et al. (2007) prepared a cap system equipped only with six dry electrodes and a dry reference electrode. The information-transmission rate of their new system was only 30.8% slower than that of their previous experiments using caps with 64 wet electrodes on the same participants. They stated that the advantages of their system were the ease of preparation for EEG measurements and the long-term monitoring capability.

Various types of dry electrodes for EEG measurements have been developed, and one type is a bundle of microneedles (Griss et al., 2001; Chiou et al., 2006; Ruffini et al., 2006; Ng et al., 2009). In this case, microneedles pierce the outer skin layer (*Stratum corneum*), which has high impedance characteristics, and contact the *S. germinativum* layer where living cells exist and are electrically conductive. Therefore, using these electrodes does not require skin preparation. Griss et al. developed such an electrode with a spiked silicon electrode array using a microfabrication technique. Furthermore, Ruffini et al. developed an electrode with an array of multi-walled carbon nanotubes. Although they reported that their electrode was useful, the microneedles must be designed carefully to prevent cell damage.

Conductive textile-based electrodes have been developed for ECG monitoring (Hoffmann and Ruff, 2007; Beckmann et al., 2010). They are comfortable and also durable for long-term use because of their softness. However, these textile-based electrodes are hard to use on hairy sites. Above all, Lin et al. (2011) developed an EEG electrode made of urethane foam covered with a conductive polymer textile. They reported that their electrode can be used on a hairy site.

A popular dry electrode is the pin-based type, which has a metal-pin that contacts the skin. Zander et al. (2011) used a head cap with three pin-based electrodes, a reference electrode, and a ground electrode for their BMI experiments. They concluded that their dry electrode system showed no degradation in EEG and BMI performance in most cases. Liao et al. (2011) also used a metal-pin electrode system. They obtained similar brain waves from both dry and wet electrodes in simultaneous measurements. Sellers et al. (2009) compared pin-based and paste-based electrodes by simultaneously mounting these electrodes on a specially developed headpiece. The EEG signals of these two types of electrodes were almost identical, and the BMI classification accuracy was also almost identical while performing a copy-spelling task. Although these dry electrodes have been reported to be useful, we are concerned that they may cause pain or may injure the surface of the patient's head when hard solid electrodes are used, particularly when the patient is lying on a bed with his/her head resting on the pin electrodes.

We have developed several types of electrode for BMI (Toyama et al., 2011a,b). In this study, we prepared a specially designed conductive solid-gel as an electrode material for BMI. The solid-gel retains moisture and is not sticky like paste (here we use "gel" as a chemically defined term). We selected the ingredients carefully to produce a moisture-retaining solid-gel. The solid-gel contained a liquid comprising carboxymethylcellulose (CMC), $CaCl_2$, glycerol, and pure water. The superior wettability of our solid-gel was attributed to the nature of the ingredients. $CaCl_2$ and glycerol are water-absorbing materials. The weight of these materials increases when they are exposed to a normal room environment. Due to an electrochemical reaction, a combination of Ag/AgCl electrodes and KCl-containing liquid or solid-gel is usually recommended as an electrode material to measure biopotentials. The potential between the electrode and solution in contact with that electrode is constant for a long period. By contrast, the electrode signal is apt to drift in the long-term when we use non-recommended materials, such as $CaCl_2$. However, this problem has essentially been alleviated with modern circuit technology. Today, we have extremely high-precision analog-to-digital converters (ADCs) for medical research and clinical measurement systems (Aksenov et al., 2001). For example, when a 24-bit ADC is used to capture the voltage signal, a signal with $0.12\,\mu V$ precision and $\pm 1\,V$ full range can be obtained, which is sufficient to cover the drift due to the electrochemical reaction at the electrode surface. Therefore, operators of the measurement system can use digital filters to subsequently obtain brain waves.

Here, we examined the usefulness of a new system with the in-house conductive solid-gel-based electrode by comparing it with in-house metal-pin-based electrodes and conventional paste-based electrodes.

MATERIALS AND METHODS

SOLID-GEL ELECTRODE

The solid-gel chip (**Figure 1**) was made of CMC sodium salt (MW, 700 kDa; Sigma Chemical, St. Louis, MO, USA), calcium chloride dihydrate (Wako Pure Chemical Industries, Ltd., Osaka, Japan), glycerol (Nakalai Chemicals, Kyoto, Japan), and pure water. The solid-gel contained 10.9, 38.0, 7.6, and 43.4% of these compounds by weight, respectively.

METAL-PIN ELECTRODE

The structure of the metal-pin electrode is shown in **Figure 2**. Seven metal-pins extended from one side of a cylindrical main body, which was made of epoxy resin. Each metal-pin was composed of a center rod, an outer sheath, and a spring. The rod could be forced inward under pressure, so it was harmless to the scalp. The effective area of the rod tip was enlarged by sandblasting to decrease the contact impedance between the rod and the skin. Additionally, a wire was fixed at the end of the rod instead of at the outer sheath to minimize the friction noise caused by sliding between the center rod and the outer sheath.

COMMERCIALIZED PASTE

In this experiment, we also used a conventional paste (ABRALYT 2000; abrasive electrolyte-gel; EASY CAP, Munich, Germany) as a control material to compare its usefulness.

HEAD-MOUNTED CAP

We developed an original head-mounted cap with 12 electrode sockets (**Figure 1**) for use with solid-gel electrodes, metal-pin electrodes, and commercial paste. Each electrode socket had a silicone-based grommet equipped with a through-hole where the solid-gel-based, metal-pin, and paste electrodes were inserted. During EEG measurements, one electrode was used as a reference. The diameter and depth of the through-hole were 15 and 8.5 mm, respectively. When using a solid-gel chip, the chip was inserted

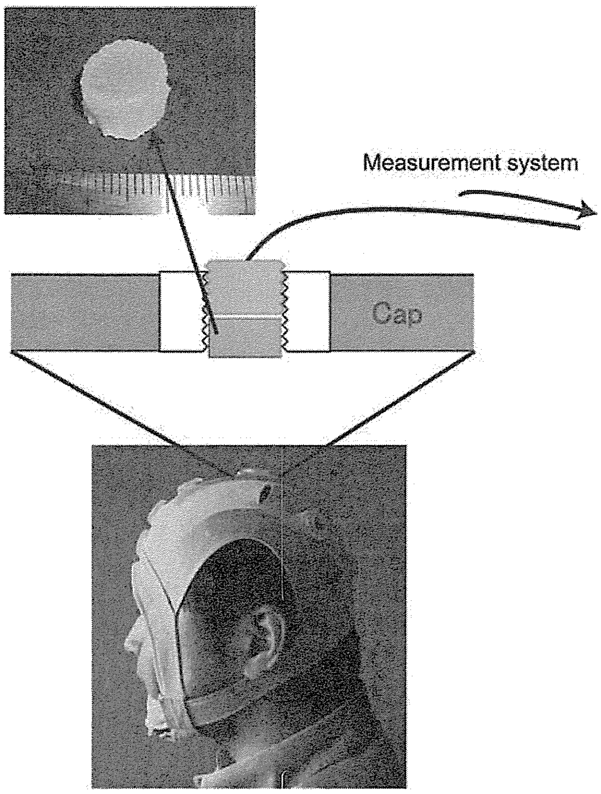

FIGURE 1 | Photograph of the originally developed head-mounted cap, which has 12 electrode sockets. One of the electrode sockets on the cap is enlarged to explain how the solid-gel is used. The solid-gel chip is loaded in the through-hole; the hole is then plugged with an electrode plate. The diameter of the chip was approximately 12 mm, and the height was approximately 7 mm.

into the through-hole of the grommet, which was plugged with an electrode plate. The body of the electrode plate was made of epoxy resin and was cylindrical in shape, and its outer wall had concentric grooves. The inner side of the through-holes of the cap had concentric grooves with the same pitch as that of the plate, so that the plate was held tightly in the through-hole. A flat Ag/AgCl plate was attached to the bottom of the plate, and an electric wire protruded from the rim of the top. The electric wire was solder-mounted on the Ag/AgCl plate at the inside of the plate and penetrated it. Wire terminals were connected to the brain-wave-measurement system.

MEASUREMENT OF VOLUME RESISTANCE: SOLID-GEL VS. PASTE

The volume resistance of the solid-gel and paste was evaluated using a rectangular measurement cell in which the facing sides were a pair of plain electrodes. The cell was filled with sample material, and its impedance was evaluated with a frequency response analyzer (S-5720B, NF Corp., Kanagawa, Japan).

EVALUATION OF VISCOELASTICITY: SOLID-GEL

The dynamic viscoelasticity of the solid-gel was evaluated using a rheometer (NDS-1000, Taisei, Saitama, Japan). The complex modulus of a sample was obtained from the dynamic displacement response on applying sinusoidal pressure (3 Hz). The dynamic viscoelasticity of a silicone rubber plug (E-02, Taiyo Kogyo, Tokyo, Japan) was also measured as a reference sample.

EVALUATION OF MOISTURE-RETENTION PROPERTY: SOLID-GEL VS. PASTE

The moisture-retention property of the samples was evaluated by measuring their weight under a controlled atmosphere. Each sample filled a small cylindrical plastic cup (diameter: 19 mm; depth: 22.5 mm) to the top. Then, the cups were put into a thermo-hydrostat (TPAV-48-20, ISUZU, Tokyo, Japan) without a cover, and the cups were weighed every 2 h. Temperature and relative humidity were constant at 23°C and 40%, respectively. Two kinds of liquid sample were prepared to contrast the moisture-retention property of the solid-gel and the conventional paste. One liquid contained 42.7, 8.5, and 48.7% of $CaCl_2 \cdot 2H_2O$, glycerol, and H_2O by weight, respectively. The other liquid was a 3 M KCl/H_2O solution.

IMPEDANCE EVALUATION: SOLID-GEL VS. METAL-PIN VS. PASTE

The participants in the electrode impedance evaluation were 11 healthy adults (six males, five females; age range 20–39 years; average 28.2 years). The experiment was approved by the Institutional Review Board, and all participants provided written informed consent according to institutional guidelines. The impedances of the solid-gel, metal-pin, and conventional paste electrodes were measured simultaneously by positioning these electrodes at P3, Pz, and P4, respectively.

BMI MEASUREMENTS: SOLID-GEL VS. METAL-PIN

For the P300-BMI tests, four healthy males (age 26–39 years) were recruited as participants. The experiment was approved by the Institutional Review Board, and all participants provided written informed consent according to institutional guidelines. The participants were required to input 15 hiragana characters from the Japanese alphabet using a row and column flicker panel with an 8 × 10 matrix in each condition. For this purpose, we modified the P300 speller (Farwell and Donchin, 1988), which uses the P300 paradigm, which presents a selection of icons arranged in a matrix. The participant focuses attention on one of the icons in the green/blue flicker matrix as a target, and each row/column of the matrix is intensified in a random sequence. The target stimuli are presented as the rare stimuli (oddball paradigm). P300 responses to the target stimuli were elicited, and the extraction and classification of these responses can be used to get the target. One complete cycle of eight row intensifications and 10 column intensifications constitutes a sequence. Online performance was evaluated, and each letter was selected in a series of 10 sequences. Eight-channel (Fz, Cz, Pz, P3, P4, Oz, PO7, PO8) EEG data were recorded using an in-house cap and an amplifier (g.USB amp, Guger Technologies, Graz, Austria). All channels were referenced to the Fpz, and grounded to the AFz electrode. Fisher's linear discriminant analysis was used for classification purposes. The details of experimental setting were same as in our previous study (Takano et al., 2009).

RESULTS

We first evaluated the moisture-retention property. **Figure 3** shows the time-dependent change in the weight of our solid-gel. The decrease in the weight of the liquid, which was the electrolyte of

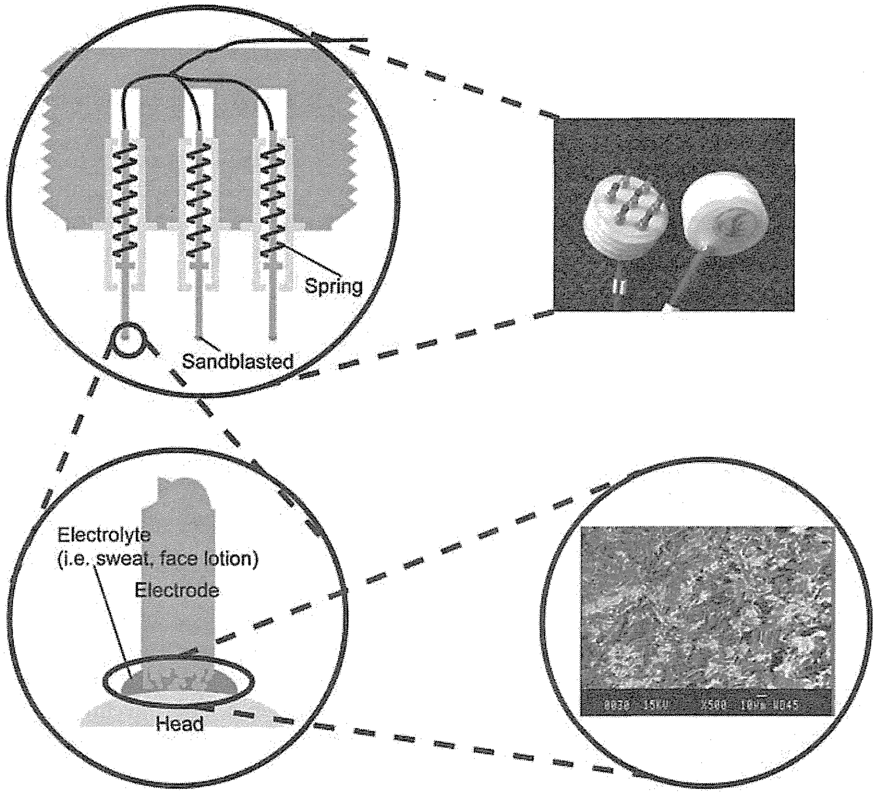

FIGURE 2 | Photograph of the metal-pin electrodes and illustration of the electrode structure. The electrode has seven retractable pins. The tip of each pin was sandblasted to enlarge the effective surface area (see inset scanning electron micrograph).

the solid-gel, was less than that of the KCl solution that is normally used for conventional electrodes. The decrease in the weight of the solid-gel material was also smaller than that of conventional conductive paste, suggesting that the solid-gel remained wet for more than 10 h in the dry environment.

The fabricated solid-gel chips were not sticky, but elastic. The complex modulus was 105.4 kPa, whereas that of the silicone rubber plug was 2088 kPa. Moreover, the volume resistivity of the solid-gel was about 13.2 Ωcm, which is sufficiently low to obtain brain waves. For comparison, the volume resistivity of the conventional paste was measured as 64.8 Ωcm. Before inserting the solid-gel chips into the through-holes of the head-mounting cap, we pushed aside the hair appearing at the bottom of the through-holes. However, this process was not laborious when we became accustomed to it, and it took 30–60 s for each chip setting, even in the worst case. The solid-gel chip was deformed when it was inserted into the through-hole and exposed to pressure from pushing the electrode plate with a finger, thereby penetrating the hair mesh and attaching to the scalp skin surface. The total setting time required before the measurement was 5–10 min.

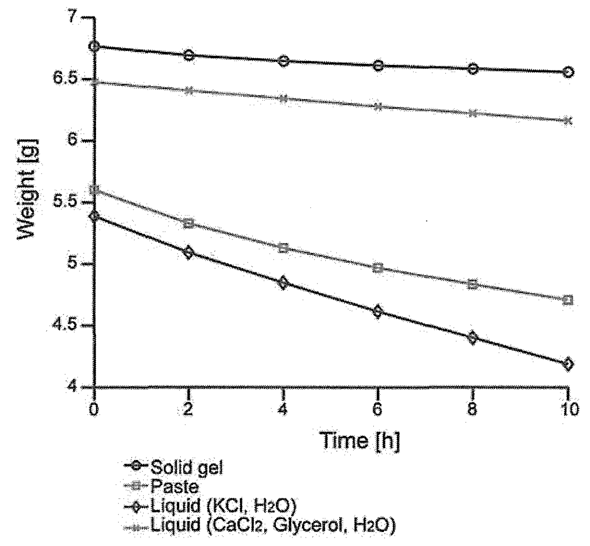

FIGURE 3 | Time-dependent changes in the weight of the solid-gel and other materials. Data of four materials were taken simultaneously.

An impedance evaluation test was carried out to evaluate electrode attachment. **Figure 4** shows the impedance time course between the reference and the brain-wave collecting electrodes including the newly developed electrodes. Although there were 11 participants, some data were omitted. The data from two females were omitted because the impedance of the paste-based electrode abnormally increased during the measurement. The impedance for one person was 92 kΩ at 3 h and 116 kΩ at 4 h, and that of the other person was 468 kΩ at 3 h and 5654 kΩ at 4 h. In these cases, we noted that the paste had dried. Data for the metal-pin electrodes in six individuals were also omitted due to irregular impedance values from the start; the main reason was likely the thick hairs between the electrode and scalp, which would cause poor contact between them. Therefore, data of nine participants (six males, three females) for the paste- and gel-based electrodes and five participants (four males, one female) for the metal-pin electrodes remained.

The initial impedance of the solid-gel-based electrode was slightly higher than that of the paste-based electrode, but it decreased gradually and was sufficiently low within 1 h. The impedance ranged from 3 to 25 kΩ (typically 10 kΩ). Moreover, it was noticeable that only the impedance of the solid-gel-based electrode decreased continuously. In two cases, we continued impedance measurements with the solid-gel-based electrode and discovered that the impedance was almost constant for at least 9 h in both cases (data not shown). Furthermore, from the data for the five participants in whom we evaluated the impedance with all three electrode types, ANOVA and the *post hoc* Tukey–Kramer test revealed that the impedance (at 4 h) of the metal-pin electrode was significantly higher than those of the other electrodes $[F(2,8) = 12.01, p = 0.0039]$. A similar tendency in the impedance behavior was observed with a slightly different solid-gel containing $MgCl_2$ instead of $CaCl_2$ (data not shown).

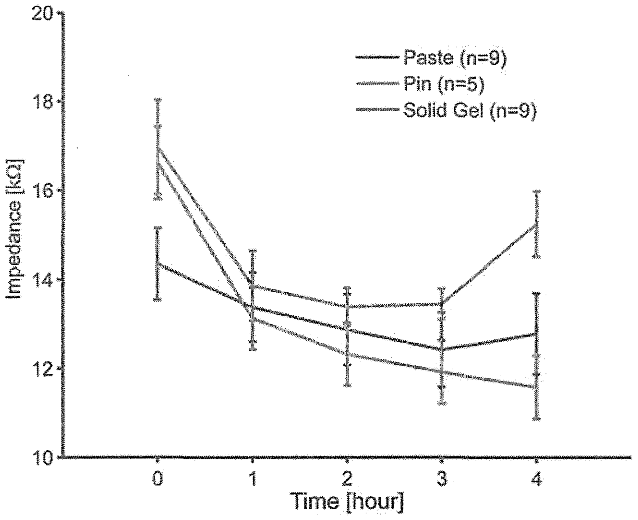

FIGURE 4 | Time course of the electrode impedance of the solid-gel, metal-pin, and conventional paste-based electrodes mounted on the head. Nine participants participated in these experiments at most. However, data for two participants using to the paste-based electrode was omitted, because the values were abnormally high due to drying.

After checking electrode impedance, we successfully obtained brain waves with the solid-gel-based electrodes. As shown in **Figure 5**, we observed similar α-waves and the spike-like waves corresponding to eye blinking during the measurements using the solid-gel- and paste-based electrodes.

Furthermore, we examined the use of the electrodes for operating a P300-BMI to input hiragana characters (**Figure 6**). With the metal-pin electrode, the mean accuracy was 85% ($n = 4$, 73.3–92.3%), whereas with the solid-gel-based electrode, the mean accuracy was 86.7% ($n = 4$, 80–92.3%). These results showed the potential of these electrodes for practical use as a BMI system in individuals with disabilities.

The conventional paste was apt to dry, especially peripherally, where it was exposed to the atmosphere; it was also difficult to remove without washing the hair after use. By contrast, the solid-gel-based electrodes had superior wettability throughout the extended measurements. The solid-gel remained wet for more than 9 h after the measurement; consequently, it was easy to remove, and almost no residual solid-gel was seen after use. Moreover, we observed no skin problems after using the solid-gel-based electrodes in our experiments.

Our solid-gel chips can be stored for more than 3 months at room temperature without any significant change when packed in a sealed container, suggesting the practical usefulness of our solid-gel chip.

DISCUSSION

We prepared a conductive solid-gel-based electrode and a metal-pin-based electrode. An examination of the weight change in

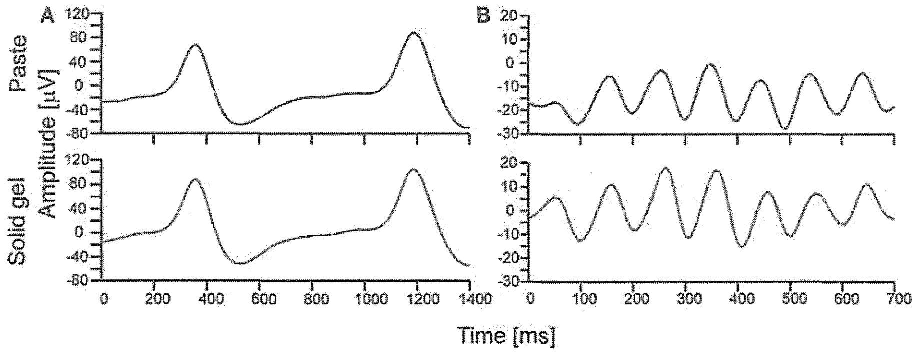

FIGURE 5 | Typical brain waves observed during simultaneous measurement using the solid-gel- and paste-based electrodes. **(A)** Brain waves observed during intermittent eye blinking. **(B)** Alpha waves. The upper and lower waves in each graph correspond to the signals obtained with the paste-based and solid-gel-based electrodes, respectively. The signals were collected with an in-house EEG amplifier (24 bit, 1024 Hz). The represented data were obtained through an eighth-order bandpass filter (1–15 Hz).

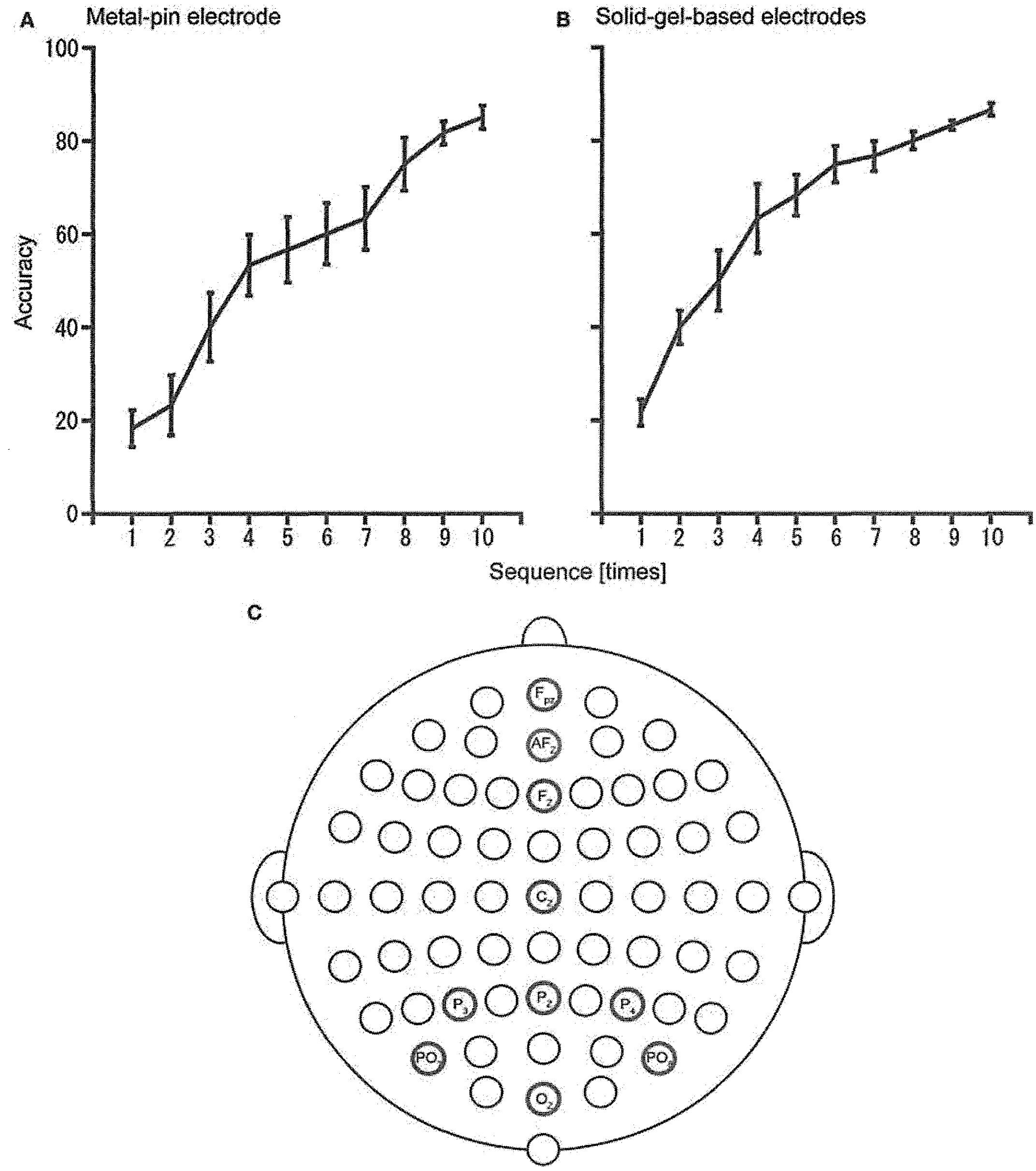

FIGURE 6 | Results of the P300-brain–machine interface (BMI) experiments using (A) metal-pin electrodes and (B) solid-gel-based electrodes. The configuration of electrodes is represented in **(C)**. Data were obtained from the same participants ($n = 4$).

the solid-gel material under a controlled atmospheric environment revealed superior retention of wettability by our solid-gel compared to that of conventional paste. The electrode impedance measurements were comparable between the solid-gel-based electrode and the conventional paste-based electrode, whereas the impedance of the metal-pin electrode was higher than that of the newly developed electrodes. Furthermore, we obtained almost equivalent signals with the solid-gel-based and paste-based electrodes during simultaneous brain-wave measurements. Finally, we successfully performed P300-BMI using both the metal-pin and solid-gel-based electrodes.

The solid-gel is elastic and is soft enough for use on human skin. Boyer et al. (2009) reported that the complex modulus of the skin on the arm is 10.7 ± 2.64, 8.09 ± 1.84, and 7.17 ± 2.06 kPa for participants 18–30, 31–50, and 51–70 years old, respectively. The complex modulus of the solid-gel was 105.4 kPa, whereas that of silicone rubber was 2088 kPa. Although the scalp is slightly harder than the arm skin, the silicone rubber was much harder than either of these.

All ingredients used in our solid-gel are food additives. CMC is used as a thickener in ice cream (Regand and Goff, 2002), and glycerol is used as a sweetener or moisturizer. Calcium chloride is used to prepare a coating material on fruit (Oms-Oliu et al., 2010).